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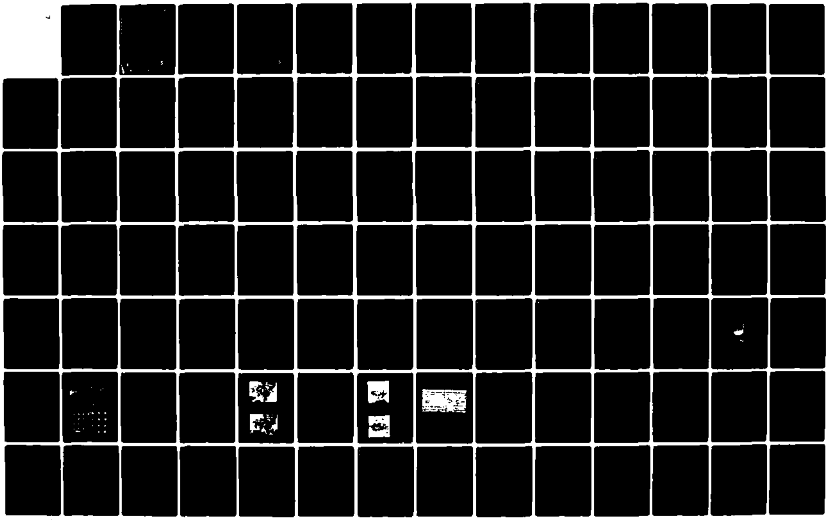

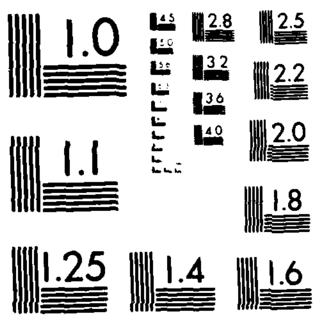
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FINAL TECHNICAL REPORT

ON

DEVELOPMENT OF A 3-D MICROSCALE TOPOGRAPHY SYSTEM

PHASE I

S. S. GASSEL
B. B. AGGARWAL
T. M. YONUSHONIS

SKF REPORT NO. AT83D001

SUBMITTED TO:

OFFICE OF NAVAL RESEARCH
800 N. QUINCY STREET
ARLINGTON, VA 22203

SUBMITTED UNDER CONTRACT NO. N00014-79-C-0792

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SKF TECHNOLOGY SERVICES
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KING OF PRUSSIA, PA

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1 March 1984

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PHASE I

Dec.'83

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I. INTRODUCTION

The need for a quantitative description of the topography of surfaces has grown in proportion to the appreciation of the relationships between surface texture and surface functional performance. Examples where such characterization is required are numerous [1]. While surface microgeometry has been examined by a variety of instruments [2] and much qualitative information is available [3], a detailed 3-D quantitative description of surface topography is difficult to obtain.

Quantitative surface measurements are currently obtained by multiple line traces using a mechanical stylus [4]. This measurement is limited by the finite stylus tip radius (2.5 μm) as well as the time (minutes) required for a single line trace. In addition, physical contact between the stylus tip and surface can destroy certain features of significance in characterizing surface performance [5]. Other approaches such as specular reflection, various interference methods, shadow casting techniques and optical profilometry are either too cumbersome and/or qualitative. The use of the monoscopic SEM images to define surface topography while offering greatly increased horizontal resolution (~2 orders of magnitude) compared to the stylus and a high speed of implementation ($6.25(10)^6$ image points in seconds), lacks a calibrated altitude reference [6].

A consideration of the features desired in advanced 3-D surface measurement systems will define the hardware requirements. In addition to providing resolution, accuracy and precision comparable with currently available instrumentation, the development of a new generation surface characterization tool should strive to incorporate the following capabilities:

- Speed compatible with interactive generation of surface maps.

- Non-contacting hardware to preclude disruption of significant surface features and distortion of the actual topography.

- Provide a point-by-point, 3-D description of the surface amenable to processing with a digital computer.

- Potential to investigate other aspects of surface texture which impact its functional performance (e.g. chemistry, metallurgy).

- Potential for total automation.

A system which uses sterescopic image pairs generated by a SEM to define surface topography enables attainment of all the preceeding objectives.

This report summarizes the work done in Phase I of a program to develop a 3-D surface measurement system using a stereo pair of SEM images. Phase I consisted of a comprehensive literature survey to define the state-of-the-art in stereo-microscopy (Task 1) and a set of experiments to establish the feasibility of the proposed method (Task 2). Section II summarizes results from Phase I. Section III describes the results of the literature survey which fulfills the objectives of Task 1. Details on the computerized literature search are provided in Appendix A. The proof-of-concept experiments are discussed in Section IV and Appendix B. Finally, a description of the system to automate stereometry and construct a viable 3-D surface measurement tool is provided in Section V.

II. SUMMARY OF PHASE I

A comprehensive survey (literature and personal communications) has been conducted to ascertain the current state of knowledge regarding stereometry on the microscale. Results of interests are high-lighted below.

1) SEM stereometry has been successfully implemented by Boyde [7] in the biological sciences. We have reproduced this hand-measurement procedure at SKF on a standard [8].

2) Major sources of error have been identified [7,9], and procedures to avoid these problems have been established. At high magnification (>500X), the stage tilt measurement and elimination of image rotation are critical parameters. The stage tilt can be calibrated [10] to rid of the effect of play in the drive mechanism. Elimination of image rotation about the beam axis during tilt requires an eucentric tilt stage. Eucentric tilt motion maintains the field of view as the specimen is tilted. The required stage is not commercially available. Distortion (non-linearity) of the CRT and any subsequent photographic distortions can be eliminated through the use of an internal scale [7]. However, in the fully-automated system described subsequently, these problems are eliminated because no photographic image is involved in the data acquisition process.

3) Resolution of the SEM-stereo procedure is two orders of magnitude better than the stylus in the horizontal direction

(~ $100 A^o$ = .4 μin). Vertical resolution of ~ $250^o A$ = 1.0 μ in. can be achieved if photogrammetric self-calibration techniques [11] are employed. Commercially available SEM's with a smaller beam diameter, say $25^o A$, would enhance the resolution by a factor of 1/4.

4) Precision of the manual procedure was reported in [10] to be approximately 1%. This is consistent with our results using a standard (Appendix B). Accuracy of the procedure has not as yet been definitively assessed.

5) Correlation software, required for the automation of the stereo mapping procedure, has been successfully utilized in the case of aerial photogrammetry [12]. Algorithms required to match physical points on the stereo micrographs will be variations of these particular programs. Here, the points must match raster line to raster line limiting the search domain. In addition, private communication with Mr. Doug Petri from JPL provided information that experimental software has surpassed the pattern recognition capability of the human eye-brain combination.

6) Postprocessing software available for extracting physical surface features is typically cumbersome to implement, due to its general purpose architecture, and requires large core storage capability.

The proof-of-concept test was implemented in two steps. In the first test, the SEM technique was calibrated by measuring a "standard" with the Talysurf IV and via photogrammetric evaluation of the corresponding pairs. The standard is a ground M50 ste^l specimen with a stepped-down area obtained by electropolishi . The step height was assessed by hand measurements from stere pairs. Details of the procedure are provided in Appendix I Subsequently, we proceeded to obtain stylus measurements of h specimen for comparison. In the second experiment, measurements were made on a specially prepared aluminum specimen using a stylus (Talysurf IV) and the stereo technique. Contours were generated with each method and compared. The stereo technique exhibited 10% error compared to the stylus results.

III. STATE-OF-THE-ART IN STEREOMICROSCOPY

III.1 Literature Survey

A literature search was undertaken to define the state-of-the-art of stereomicroscopy; quantitative surface topography on the microscale using SEM generated stereo pairs. Topically, this field includes: Analytic Photogrammetry, Scanning Electron Microscopy, Digital Image Processing and Automatic Pattern Recognition. The union of these sciences, provides the technological base for development of an automated 3-D SEM-Stereo Topography System, the long-range goal of this program.

This report details only the computerized literature search. Additional materials were acquired by hand searches and through personal communications with other researchers active in the field. Included in Appendix A is a description of the search strategies employed, quantification of results, as well as an evaluation of the various data bases surveyed.

The survey was conducted using the following seven data bases:

COMPENDEX	(Engineering Index)
DISS	(Dissertation Abstracts)
INSPEC	(Science Abstracts)
SSIE	(Smithsonian Science Information Exchange)
NTIS	(National Technical Information Service)
NASA	(National Aeronautics and Space Administration)
DDC	(Defense Department Command)

These seven data bases provided for a comprehensive survey of the existing state-of-the-art in stereomicroscopy. Over 700 references were identified and screened. Of these, nearly 100 were found to be directly applicable to this project and are reviewed in the following sections.

III.2 Quantitative Surface Measurement Methods

Methods used for surface topographical measurement are diverse and include scanning electron microscopy, interference microscopy, capacitance probes, surface reflectance, oblique sectioning and profilometry (stylus method). Monoscopic SEM images can provide important qualitative information about surface topography, but it is difficult to obtain quantitative information. Interference microscopy is used to generate contour maps of the surface but the vertical resolution is fixed at about 0.25 microns [1]. For tribological purposes, the stylus method is the most widely used approach to obtain two-dimensional surface profiles. Methods used for surface measurement have been reviewed by Green [8], Greenwood [1], Richards [7], and Thomas [10]. The stylus method and some non-stylus methods are reviewed below.

III.2.1 Stylus Method

In the stylus method, the surface profile is obtained by using a profilometer. A profilometer consists of a lightly-loaded stylus connected to an electro-mechanical transducer. As the stylus traverses the surface, the vertical movement of the stylus is recorded with respect to some appropriate datum.

The transducer produces a voltage analogue of the surface. Signal processing of the stylus output is straightforward. Analogue processing of the signal has been reviewed by Greenwood [1]. However, due to the widespread use of digital computers, digital processing of the transducer signal has become common. Here the output of the transducer is processed through a suitable analogue to digital converter and recorded to obtain a permanent numerical record of the surface profile.

There are a number of documented problems associated with the stylus method [1,5,8,9,15]. The contacting stylus may damage the surface [9,15]. However, Williamson [5] has reported that for a lightly loaded, high resolution stylus, the surface damage is not significant even for soft metals like aluminum. the stylus may not reproduce the surface accurately because of the finite size of the stylus, particularly for sharp peaks and valleys. Greenwood [1] has shown that all convex radii on the surface are increased by the stylus radius while all concave radii are decreased by the same amount. The effect of stylus radius on surface profiles has been discussed in greater detail by Radhakrishnan [3,4]. Another factor that limits the profile resolution is mechanical vibration of the stylus, placing an inherent speed limit on the instrumentation.

A stylus trace of a surface is a single two-dimensional profile and it is difficult to generalize a two-dimensional profile into a three-dimensional surface. A peak on the profile is not necessarily a summit on the surface. Two adjacent peaks on the surface profile may not be real summits but shoulders

of the same higher summit off to one side of the traverse. However, Williamson et al [13] and Williamson [5,6] have used the stylus method to produce contour maps of the surface by making a set of parallel traverses at equal spacings and obtaining an array of surface profiles. Such arrays of profiles, obtained by relocation profilometry [11,12], are a more accurate representation of a rough surface than a single surface profile.

The major advantages of the stylus method are minimal surface preparation and superior vertical resolution (~0.0025 μm = 25°A). The major disadvantages include surface damage for soft specimens, slow speed, and poor horizontal resolution. Typical values of horizontal resolution are 1μm; 3 orders of magnitude larger than in the vertical direction. This imposes limits on the calculation of surface slopes and curvatures, parameters of recognized significance in concentrated contact performance.

III.2.2 Non-Stylus Methods

A large number of non-stylus methods have been used for surface roughness measurement. Some offer a radically different approach to surface measurement while others are similar to the stylus methods except that the mechanical stylus is replaced by a non-contacting optical [16,17] or capacitive [18] probe.

Scatterometry has been used for surface measurements [19-29]. In interference microscopy [19], two incident beams of light are used to obtain a fringe pattern which in turn yields statistical information about the surface. In single beam systems [20-29], the angular distribution of the scattered light is used to map the power spectral density of the surface. Both the

single beam and multiple beam methods cover large areas of the surface being measured. Therefore, they are particularly suited to drawing contour maps of surfaces and estimating statistical parameters like the rms roughness. These methods are not suitable for obtaining surface heights at particular locations. The resolution of the scattering method depends on the wavelength of the incident light beam and ranges from 0.1 to 100 Angstroms for wavelengths in the visible range.

A high-precision laser based surface measurement system for super smooth surfaces was reviewed briefly in Industry Week [30]. The system employs two lasers and claims to detect surface-height variations down to a single angstrom (10^{-10} meter) on metal or glass surfaces. The surface being scanned is placed face-down on a turntable with a hole in the middle. Two laser beams polarized at right angles to each other, are focused through the center hole onto the surface being inspected. As the turntable rotates at 2 rpm, one beam traces a tiny circle while the other is directed straight up to the center of this circle. (This serves as a reference). The laser beams are reflected from the surface of the piece being inspected to a detector, which measures the difference between the two beams caused by surface irregularities. Computers then analyze these data.

Hologrammetry presents a potential for simple mapping devices [31]. An interference fringe pattern obtained by the interference of a reference beam with the light reflected from the object

is recorded on a hologram plate. A reconstruction beam parallel to the reference beam is used to illustrate the hologram plate and create a virtual life sized image of the object. Capabilities of holographic systems include digital mapping, contour maps and cross-sections. Interference fringe patterns on the hologram plates can be used to obtain the values of statistical parameters used to measure surface roughness [32,33].

Electron microscopes, both TEM and SEM, are also used to study rough surfaces [34, 35, 36]. A single SEM image provides valuable qualitative information about surface texture. However, to extract quantitative topographical information requires use of an altitude reference [14]. Lebiedzik et al [36,38] devised a method where an array of backscattered detectors are used to determine the slope and orientation of each surface spot scanned and reconstruct the surface. Hoover [74] and Smith [75] marked the SEM specimen with a line of organic contamination and heavy metal, respectively, and correlated the line's distortion due to specimen tilt with surface heights. Hersener and Ricker [76] and Holburn and Smith [77] adopted the method of measuring height by monitoring the objective lens current as the beam is kept in focus.

An alternative approach is to use a stereo pair of SEM images to extract three dimensional topographical information [37,39,40,41]. The latter approach is seen as favorable because of its universality compared to other SEM related methods, provided that the procedure can be automated. Automated, three dimensional observation by SEM stereometry provides several advantages

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- High speed, non-contact instrument compatible with a digital computer.

- Twice the horizontal resolution of the stylus.

- Potential for total material characterization.

In summary, three dimensional topographical measurements via SEM images provides an opportunity for a next generation surface measurement tool.

III.2.3 SEM Stereo Techniques - Measurement Methods

The principles employed in stereomicroscopy are founded in the field of photogrammetry. Two images of a surface are prepared at different orientations. This induces a parallax shift to the image points which is related to their relative heights. By measuring the parallax, three dimensional information can be extracted from pairs of two dimensional images.

As reported by Boyde [43], the first photogrammatic work with the SEM was done by Wells in 1957. This effort was patterned after the tilt method of stereo pairs using a transmission electron microscope (TEM) reported 13 years earlier (See Heindenreich and Matheson [44]*.) Wells in 1960 [45]

---

* The delay is attributed to the lag in the development of the SEM compared to the TEM.

described the "perspective error" which arose by assuming parallel projection optics when taking pairs at low magnification. The error, in fact, was due to the erroneous assumption, since the SEM is a central perspective system. At high magnification this difference is not measureable. Careful evaluation of SEM projection geometry began with Lane [46] in 1969. This work led to complicated formulae for extracting heights from stereo pairs obtained by specimen tilt. Both two and three (specimen plane does not intersect the tilt axis) dimensional cases were considered at high magnification. Cripps and Sang [47] extended this work by deriving analogous relocation equations for the specimen translation case. It was noted that this method suffers in its ability to resolve small heights due to CRT resolution limits. Comments regarding the accuracy of the tilt method were also contributed. It was pointed out that the percent error in height measurement's proportional to the percent error in the tilt angle difference.

Practical problems in SEM stereometry and methods for their solution were discussed by Boyde [48]. The importance of calibrating magnification and stage tilt angle were examined. Inherent non-linearity in CRT displays was explored. The use

of an internal scale to rid of this problem, as well as distortion due to unstable photogrpahic emulsions, was described. Rotation of the second image after tilting was identified as another source of error. These, in the absence of an image rotation module or eucentric stage, must be calibrated out. Finally, various instruments for plotting (discussed in detail in Section 1.4) surface contours and profiles were described.

It is significant to note that up to this point formulae for computing relative heights varied from writer to writer. The apparent discrepancies were found to be a function of the selected reference plane for measuring heights. A comparison of certain "natural" alternatives were discussed by Howell and Boyde [49] in 1972. They recommended three reference planes: the right, left and mean image planes. Such references are suitable for biologists interested in the specimen features but are inappropriate for tribological applications. The SEM stub reference plane, employed by Lane and then by Cripps and Sang, provides surface heights as taken by a stylus. This is the "natural" reference for the surface metrologist and for the tribologist interested in characterizing surface roughness and its influence on contact performance.

Another approach to creating SEM stereo pairs was pioneered by Dinnis [50] in the early seventies. This method involves "tilting" the electron beam rather than the specimen. The beam is deflected with an additional set of scanning coils so that it selects the same target (pixel point) but can approach that spot from two different angles. The images appear to have been generated by scanning the specimen at different tilt angles. This concept was improved by Boyde et al [51]. The special scan coils are placed in the final lens bore enabling the SEM chamber to be uncluttered. The system was used for real-time three dimensional display. This led to a configuration with dual TV displays for the pairs which are viewed with a variety of stereoscopic systems. One novel observation method was to view superimposed pairs on color TV monitors [52]. The left image was [illegible] in green and the right image in red. With appropriate "glasses" the 3-D images could be viewed by any number of observers. This is analogous to the 3-D movies made popular during the nineteen fifties. Further details on real-time TV stereo systems may be found in Boyde's excellent review paper [53] and the text by Goldstein et al [54].

The ability to make accurate measurements of the third dimension from SEM stereo pairs had evolved as a method, but its manual implementation was tedious and impractical. It took too long to extract meaningful data about the surface. this was true, even in the biological sciences, where feature extraction is of primary concern. The situation was worse for the physical sciences (e.g. tribology) where surface topography is often characterized in terms of geometric statistics. Computation of rms values, or spectral moments, from stereo pairs remained intractable. The need for automated measuration was obvious, and this led to the introduction of digital image processing concepts into stereometry.

A semi-automated method was described by Boyde [55] in 1974 where the Quantimet Image Analysis system was used to do on-line measurements from the Quantimet TV displays of the pairs. The actual procedure requires operator identification of matched points. The operator must also remember what pairs of points he selected on the first image before he matches them in the second image. the parallaxes are measured by a "cursor" and the relocation automated with a programmable calculator. The method is still extremely cumbersome and in addition, must cope with nonlinearity of the CRT display. One point of major

interest, however, is that the Quantinet and SDT TV scan systems were used as a digital scan generator with controlled scan rates. This is a powerful concept which will be fully exploited in the next generation SEM image processing systems. Improvements in the usefulness of this integrated SEM- computer system were published by Howell [56] in 1975. A BASIC programme was written to include central projection images and to rid of a attendent distortion due to scan coil non-linearities. The latter became significant with the increased beam scan angles used at low magnification.

In the midst of these advances toward making stereometry practical, the resolution, accuracy and precision of the method remained undefined. Horizontal resolution for the SEM was well established. For commercial instruments, typical values are 100A°. The theoretical vertical resolution in pairs measurements is dictated by the parallax and tilt angle differences. This is clear from the expression for the height. Relative to the left (less tilted) image plane:

$$X_L = \frac{X_L \cos\alpha - X_R}{\sin\alpha} = \frac{P}{\sin\alpha}$$

P = Parallax

α = Tilt Angle Difference

The smallest resolvable parallax difference is limited to ~100A°. The height resolution then depends on α; the larger the angle the smaller the height resolvable.

Typically, tilt angles of 6° - 10° were selected for generating pairs. This is the range of angles subtended by the human eyes when viewing at normal close distance = 25 cm. Such angles are therefore needed to view stereoscopically. Clearly, this imparts unnecessary limitation to the method, but the habit has persisted. This practice is even more surprising when it is recognized that the larger the tilt angle, the greater the apparent difference in height. This translates into better accuracy for bigger tilt angles, all other variables held constant.

The first careful study of accuracy (internal errors) was documented in a Ph.D. thesis by Maune [57] in 1973. This is not to say that major sources of error had not been identified nor solutions been achieved. In fact, many such results have already been discussed here. Rather, a systematic methodology to quantify accuracy had not been provided. As a result of using advanced photogrammatic self-calibration techniques, Maune was able to surpass accuracy in angle and height measurements for otherwise uncorrected SEM-stereo methods by 1-2 orders of

magnitude. It was demonstrated that angle and height measurements could be made with standard deviations of 0.5^{o} and $220A^{o}$, respectively.

Care must be taken when considering these results. Appropriate corrections for CRT non-linearity, such as provided by Boyde [55], would considerably help results from "otherwise uncorrected" procedures. Further, the procedure is extremely time consuming, and must be repeated for every set-up.

What is significant about Maune's results, other than the novelty of his approach, was the observation that such a method can take out errors which would otherwise be considered random. This, then optimizes the accuracy.

Precious little progress in advancing stereometry has been revealed since 1975. Several noteworthy tutorials by Boyde and Howell [58] and Boyde [53] have been published. These summarize past achievements and evaluate non-stereometric methods. The latter, and their shortcomings, are discussed in sections 1.1 and 1.2. Two exceptions are the development of commercial beam tilt systems reviewed by Pawley [59] and the creation of a semi-automated stereomicroscopy system described in [60].

The bottleneck for stereometry is the tedious manual measuration procedure. The solution is a fully-automated matching and relocation scheme. The difficulty, however, arises

in the need to replace the human eye-brain combination with an automated method to match physical points between images prior to relocation. The availability of correlation software will provide the remaining breakthrough to enable practical stereo-microscopy. This problem is addressed in Phase II of this program.

III.2.4 SEM Stereo Hardware-Measurement Systems

There exist a variety of methods and associated systems for viewing and presenting stereo pairs. It is possible for a practiced observer to fuse properly mounted stereo pairs without the aid of any stereo-viewing device. A comprehensive evaluation of pocket viewers was given by Emlen [61]. Simple lens viewers and prism viewers were also discussed by Howell [56] and more recently by Boyde [53].

For larger format photographs so-called multi-mirror (2 or 4) stereoscopes are suitable. Neubauer and Schnitger [62] and Haanstra [63] describe the two and four mirror version, respectively. More sophisticated methods for stereo observation are the polaroid filter system and the anaglyph projection system [51,64,65]. These are commonly used to display stereo slides to large audiences.

Dynamic stereoscopy has been a recent development with the advent of real time stereo TV systems [50,51]. This is achieved by magnetically tilting the beam instead of the specimen. Despite

these sophisticated viewing capabilities, measurement of surface topography is based on tedious and impractical manual procedures.

Mensuration from stereopairs may also be achieved with instruments exhibiting various levels of complexity and cost. The most straight forward approach is direct measurement with a linear scale as done in the experimental portion of this work discussed in Section IV. Reconstruction from separate measurements of pairs can also be achieved in more sophisticated fashion. The synthesis of the Imanco Quantiment Image Processing System with an SEM as described earlier (See Boyde 1974,1975) enables a "cursor-type" measurement using picture points and automated relocation computations with a desk top calculator.

All other methods documented to date produce digital or analog data from pairs and involve use of the stereoscopic observation process. These instruments make use of the floating mark or dot concept. The floating dot is merely a device by which overlapping (fused) identical features can be sighted with precision. A light spot is superimposed on stereoscopically observed pairs such that it appears in the optical plane at a matched image point.* In most photogrammetric instruments it consists of two components superimposed on each member of a

---

*See Boyde [53] for detailed explanation of how to create a floating mark with stereo observation.

stereo pair. Each dot can be moved with respect to the image to which it relates, and the two spots can be moved with respect to one another so that they overlie features which are at different separation distances.

III.2.4.1 Stereoscopes

Mirror stereoscopes with parallax measuring facilities and a combined photo-mounting platten attached to a parallel guidance mechanism so that all areas of the stereo model can be inspected and measured [66,67,68] are the simplest and most economical aid to making accurate "stereo" measurements. They are used for simple stereoviewing and for parallax measurements using the floating mark technique - the best kind is that in which the two components of the semi-silvered second pair of mirrors of a four mirror stereoscope system (as in the SB180 and SB190 series instruments)[66,67]. Simple height differences, like the depths of pits, grooves or depressions, are obtained with the unmodified instrument. Boyde [53] noted that two simple additions to such an instrument increase its usefulness enormously. Firstly, one may add a drawing stencil to the photo-platten assembly [66]. This makes it possible to trace out lines of equal parallax difference (height) by moving the photo-plattens by hand so as to keep the floating mark in contact with the ground. Secondly, one may add an X_L, Y_{LCR} co-ordinating measuring

system, which may be as simple as a piece of graph-paper fastened underneath the plattens or as a complex as a mechanical stage [69].

III.2.4.2 Stereoplotters

It is probable that most complex air survey photogrammetric plotting instruments could be used to obtain the necessary 3-D data from SEM images. Such instruments have been used for this purpose [70,71] but they are in the same range of cost as electron microscopes. Even special EM stereoplotters may be expensive and complicated [68,72].

If one examines the parallel projection equations, for example, the left photo datum plane

$$z_L = \frac{x_L \cos\alpha - x_R}{\sin\alpha}$$

He finds that there is no simple relationship between height and parallax which one can use in a mechanical plotting instrument. If, however, one modifies all the x_L co-ordinates by multiplying them, mechanically or optically, by cos α, then a modified parallax which is in constant relationship to height differences is the solution we achieve by placing a cylindrical lens close to one of the images to apply the scale correction. The resulting instruments (EMPD2[45]) were designed to deal with

a constant tilt angle difference ($\alpha = 10^{\circ}$ for EMPD1 and $9^{\circ}34'$ for EMPD2) stereo pairs and to give (1) immediate digital read-out of height differences in millimeters at the plot scale, (2) contour maps, and (3) profile sections in any chosen direction through the 3-D image, the contour interval being chosen in 'mm' at the plot scale, and the profiles to true height scale for stereo pairs taken with the designed tilt angle. The instruments were also suitable for SEM stereo work. Another example of such an instrument is the Zeiss Stereocord [73].

III.2.4.3 Other Instrumentation

Specimen X, Y and Z co-ordinates can be measured directly using the specimen stage X, Y and Z micrometers and without knowing the magnification, principal distance or tilt angle if one uses a beam-tilt stereo system. This, conceptually, is the simplest photogrammetric instrument for SEM purposes which could exist (i.e. the SEM itself). In principle, the "left" and "right" beams in the SEM cross each other at a fixed point in space. This point can be made to correspond to the place on the specimen surface under observation and whose height is to be measured. The point is identified by introducing a floating mark. This mark may consist of two components - a bright cursor mark of equal intensity displayed in the same position in both the red and the green images [52,59]; or, it may be a single black mark placed in the center of the color TV

monitor. Features are brought into register with the floating mark. Even without stereopsis, it is possible to adjust the specimen height (Z) and position (X,Y) so that the feature, in both the red and green images, is in register with the marks [52]. Using stereoscopic observation, this adjustment is achieved more rapidly and more reliably. The co-ordinates of the point brought register with the floating mark are the X,Y,Z specimen stage readings. The X,Y,Z controls could easily be attached to digitizing encoders, and the co-ordinates fed, at the press of a switch, to computer memory and/or tape store for later processing. Such a system would save greatly on photographic and accessory instrumental costs.

The future instrumentation of SEM photogrammetry according to Boyde [53] will be toward hybrid systems, which are fed out as digitized positional information to a programmable calculator and plotter. We would expand this projection to micro-computer based images processing systems with automatic pairs measuration capability. The lack of automated mensuration will prelude stereo pairs from being a practical means to characterize surface roughness. Our efforts in Phase II will overcome this critical hurdle.

III.3 Image Processing for SEM

III.3.1 Digital Processing of SEM Images: Techniques

The image produced by the scanning electron microscope consists of either a series of discrete lines or discrete points. The former refers to analogue scanning and the latter, digital scanning; each of the two representations lends itself to the various signal processing techniques available in today's technology. The objective of the following discussion will be to summarize the application of those techniques, chiefly digital, which characterize the state-of-the-art in SEM related data processing.

Major advances have been made in the area of digital processing and as a result of its application, image processing has also experienced accelerated growth. This is evidenced most noticeably in earth and space observation applications primarily through which, major developments have resulted [1,2].

Although signal and image processing capabilities exist in conjunction with other technologies, it is only of recent that these techniques have been incorporated into the SEM environment. In order to review these recent developments, it becomes necessary to define the various processing methods and their role in the variety of SEM applications.

Generally, techniques for image processing are divided into three major areas: information extraction, image enhancement, and image restoration.

Information extraction provides the user with such numerical data as number of particles, size distribution of particles, feature recognition, etc. [3]. In 1968, White, McKinstry and Johnson [4] reported a scheme for the measurement of particle size, distribution, and particle recognition for the determination of shape and orientation from SEM images. They employed an analog to digital conversion which was binary coded and applied data contouring methods. A year later, McMillon et al [5], published improvements on the earlier processing design with the addition of smoothing techniques to reduce noise content. Further developments, with the introduction of line integration techniques and least squares fitting to ellipses, were presented by Matson et al [6]. Feature identification is a central issue in the matching of stereo pairs and although the aforementioned designers involved a high degree of user involvement, more sophisticated interactive processing capable of complex pattern recognition is available [3,7].

Image enhancement refers to improvement to the image which results in a more appealing picture and due to its subjective nature, this type of image modification is not intended to provide quantitative or numerical data of any kind (but may serve in a preprocessing capacity). Enhancement techniques typically

involve reduction of noise by analogue or digital filtering, differentiation, adjustment of grey level distribution, focusing considerations, etc. In terms of SEM signals, Fiori et al [8] describes several signal processing operations which result in enhanced image detail. These include differential signal amplification, nonlinear amplification and time differentiation. The first time derivative provides enhanced contrast at the edges and will generate oblique illumination. The second time derivative enhances edge contrast and produces the appearance of vertical illumination. The super-imposition of orthogonal scans eliminates the information loss due to the directionality of the time derivatives. The application of enhancement techniques to sharpen detail, alter illumination, and insert depth appearance will usually invalidate the processed image from further quantitative analysis and in some cases bear little mathematical resemblance with the object image.

Image restoration techniques correct and upgrade images by specifying the degradation process in a mathematical form and applying the inverse numerically to the images. Jones and Smith [9] summarize many of the digital image processing operations performed in restoration of SEM images. They include correction of geometric distortion, grey-scale modification, digital filters, homomorphic filters, filters for systematic noise, Wiener or least-squares filters, filters for symmetric

images differentiation (isotrapic), averaging techniques and signal mixing. In 1969, Simon [10] applied information theory, which was formulated for the communications field, to the signal generated by the SEM and established mathematical foundation for the optimization of signal-to-noise ratio, least mean square optimization, and high-pass filtering. In these areas there have been numerous developments and contributions formulated and tailored specifically for increased capability and performance of the SEM system.

A modified optimal Wiener filter was developed by Lewis and Sakison [11]. The model incorporated an analysis of the properties of the SEM signal and the noise content (degradations process). Newbury and Joy [12] describe improvements in the SEM signal/noise ratio through statistical evaluation of the grey level distribution. This procedure allows noise to be extracted from the high-frequency (high resolution) portion of the SEM signal without utilizing probability considerations. Yew and Pease [13] have also utilized the extensive studies in information theory to grey level content in picture elements. The processing system employs an electrostatic storage device to carry out geometric correction, noise averaging (nearest neighbor averaging) and signal to noise enhancement by integration.

The advent of inexpensive mini-computer interfaces for the SEM has opened the possibility for extensive on-line processing. Software availability then provides for the implementation of a variety of image processing algorithms. Recent examples are on-line gradient processing documented by Smith et al [14], and the computation of diffractograms from two-dimensional transforms [15].

It is clear that on-line processing of SEM images via small computers will continue to evolve as the dominant means of providing image analysis capabilities. Hard wired functions are too limited and reguire regeneration of an image for each processing step. Image analysis systems are expensive and inflexible.

III.3.2 Digital Processing of SEM Images: Hardware Evolution

The developments of image analysis systems for SEM has followed a natural progression from hard wired functions to image analysers to on-line processing via digital computers. This is analogous to the hardware evolution found in other disciplines utilizing digital signal processing (e.g. photogrammetry, acoustics, radar, etc.) and is due to the rapid development of inexpensive small (mini/micro) computers.

By the early 1970's various analogue processing functions were commercially available. These included black-level suppression,

Gamma and Y-modulation. These real time capabilities suffered from obvious limitations: a) they destroyed the original image, b) they were inflexible with each operation demanding its own electronic module. Corrections to these difficulties were preposed.

Catto and Smith [1] developed a storage-display system enabling the restoration of the image at preselected stages of processing. Paden et al [2] proposed a "new generation" SEM design by utilizing digital techniques for scan generation. This system provided for brightners compensation over the full range of scan periods, allowed for control of various video processing functions and enabled alpha-numeric data to be superimposed on the displayed image.

Subsequently, image analyzers began to emerge as a means of accommodating complex image processing problems. These instruments (e.g. [3]), are specialized hard-wired counters capable of feature extraction from video pictures. At this time, the cost of an analyzer was below that of a mini-computer with sufficient disc storage for handling SEM images. However, the cost of small computer systems continued to drop dramatically, so that the flexibility offered by the digital computer was powerful incentive to develop mini-computer based processing systems.

An excellent review paper on the computer control of the

SEM was published by Herzog, Lewis and Everhardt [4] in 1974. Here, the type of interfacing required for scan control and data acquisition was described. Expectedly, computer controlled image analysis systems began to emerge (Lebiedzik [5]), described a multiple detector method for performing microtopographic characterization using the type of interface outlined in [6]. Alternatively, Oran and Gilbert configured an on-line processing system that tracks the pixel output, as opposed to controlling the scan, and digitizes the data for post-processing. Scan control is seen as preferable because it avoids the inherent processing speed problems encountered when trying to keep up with the usual SEM scan.

Recently, Jones and Unitt [7] reiterated the favorable field response to computer-controlled systems. Their review paper describes the hardware interfaces for existing systems, interactive peripherals, available software and some published systems. It concludes by describing the next step in SEM automation, the use of microprocessor for control of system functions and/or mechanical hardware.

III.3.3 Related Software

The software requirements for an automated stereometry system are numerous: scan control algorithms, image enhancement, pattern recognition and other image processing capabilities, image correlation (matching algorithm), feature extraction and digital mapping modules.

A software package to perform all the necessary pre and post processing tasks is non-existant. However, programs have been devised to perform a sub-set of the data processing operations required. In the following, a sample of available program systems and their respective capabilities will be presented.

Program system DIMES (Digital Image Manipulation and Enhancement Systems) [1] is capable of performing various grey-level manipulations, geometric alterations, image combination, and analysis for production of histograms, etc.

The VICAR system (Video Image Communications and Retrieval System) [2] contributes a general image processing system. VICAR suitable for IMB 360 or 370 computers only, does not offer a range of operations that is really suited to electron microscopy. Other serious disadvantages include: huge disk requirements and a very cumbersome non-interactive control language.

Frank and Shimkin [3] introduce image processing software designed for the SEM. SPIDER (System for Processing of Image

Data in Electron Microscopy) is a user-oriented system providing the electron microscopist with such capabilities as box convolution, point mapping operations, Fourier operations and three-dimensional reconstruction. It is an interactive system of programs closely linked to the RSX-11 operating system of PDP-11 series computers.

Another system well suited to electron microscopy is MDPP [4]. Functionally similar to SPIDER, it lacks interactive display facilities and runs only on IBM 370 computers.

A third system intimately connected with EM is SEMPER [5]. A very powerful, modular network which is implemented as a high level image processing language. It has excellent expansion capability and it is quite portable (i.e. runs in several computer environments). The overhead of the system is associated with its power. One must be imtimately familiar with the SEMPER language to use/expand its capabilities.

Software for the application of other standard digital image processing techniques for SEM is available in programs like CESEMI [6]. CESEMI, capable of feature extraction on machined surfaces, can be quite useful in quantifying the topography of scratches, pits, grooves and other tribologically significant surface features. Analogous software is offered by Lemont Scientific [7].

Beyond pre-processing of the digital image, both recognition and matching software are required to automate the extraction of microtopographic data from the stereo pairs. While appropriate software was not available for the SEM, its parent programs have evolved in the area of aerial photogrammetry.

Development of digital photogrammetry using a stereo pair of digitized images was motivated by the need to extract topographical information from terrain data obtained from a wide range of sensors. The work reviewed below was either done at the U.S. Army Engineer Topographic Laboratories (USAETL) [8-12] or for USAETL by Control Data Corporation [13] and by Bendix Research Laboratories for the U.S. Air Force Rome Air Development Center (RADC) [14,15]. While the basic approach for both the USAETL and RADC digital mapping systems is the same, the development of operating systems was molded by their respective needs.

Software responsible for image mapping and data presentation is given in [16-18]. These systems are general purpose in nature and require the support of a large mainframe because of CPU requirements. Therefore, it is necessary to develop special-purpose software packages for specific hardware configurations. Most graphics hardware manufacturers support controller software so that generation of special purpose applications packages is feasible. Similar software for computation

of surface statistics is available [19], but too extensive to be practical for this application.

The left image of the stereo pair is used as the independent image. The matching procedure consists of selecting a point on the left image and then searching for the conjugate point on the right image. Stereo matching procedure starts from a known set of matched points and proceeds along an infiltration path [9,13] on the left image until the complete image has been matched. A correlation coefficient calculated over an area centered at the estimated location of the match point on the right image is used as the matching criterion [10,14]. The location of the maximum correlation gives the actual match point. The large amount of data processing is reduced by data compaction using statistical coding techniques and specialized scanning procedures like epipolar scan [7,12]. Epipolar lines reduce the search process to one dimension. In the SEM environment, these are lines perpendicular to the tilt axis. The computation time for the correlation calculations is reduced further by parallel processors using micro-programmable flexible processors [10]. The parallel processing hardware effects a compromise between the speed of a hard-wired, special purpose correlator, and the flexibility of a large general purpose computer. The algorithms developed in [7], [9] and [11] have been modified to exploit the speed of parallel processors and an interactive

digital mapping system is being developed [13] based on the modified algorithm.

A multi-channel optical correlator system has been developed by Bendix Research Laboratories [14] for the rapid extraction of terrain elevation information from aerial photographs. The automated system matches small areas of two photographs along a conjugate pair of epipolar lines by introducing a parallax between the two photographs and calculating correlation coefficients simultaneously for the complete epipolar line by using a multi-channel processor. The two photographs are then advanced at a steady profiling velocity in a direction perpendicular to the epipolar lines. A similar mapping strategy is used in the AS-11B-X Automated Stereomapper System [15] which uses a laser scanner and parallel processor digital hardware instead of an electro-optical correlator. Use of a laser scanner yields higher signal to noise ratio than a CRT scanner, permitting a higher speed of basic data collection. Scanning time is reduced further by scanning simultaneously along many conjugate epipolar lines. The measured profiles are stored in the correlator and correlation operations are performed using digital parallel processing. Post processing of correlated data is done off line to enable each phase to proceed without impeding the other. The AS-11B-X system is capable of processing about $40mm^2$ per second.

The algorithms reviewed above can be adapted for stereo photogrammetry using SEM images. Using epipolar lines to reduce the search to a one dimensional process combined with parallel processing offers the best choice for a high speed interactive system.

III.4 Applications of SEM Stereomicroscopy: Past and Future

SEM stereomicroscopy has been used to study surface texture in both biological and physical sciences. A short review of some applications of stereomicroscopy is presented to demonstrate its general appeal. Potential new applications for the technique were also cited.

In biological sciences the SEM is used in the study of cells (cytology) and of tissues and organs comprised of cells (histology). The tissues studied include hard or "skeletal" tissues which resist gross deformation of the tissue upon removal of the minor water content [1] and soft tissues which, having a large water content, deform during the SEM scanning. Soft specimens require extensive sample preparation and, consequently, a careful interpretation of the observed images to separate out the effects of sample treatment [1]. Boyde et al [1] have developed a system to obtain three dimensional images of biological specimens.

In manufacturing technology, the SEM has been used for 3-D study of surface texture. For example, the microtopography of grinding wheel surfaces was evaluated in [2]. Surface heights ranging from 1-50 μm were mapped using a stereotop plotter for a variety of wheel operating conditions.

Unique material science applications have also been reported. In [3], strains and displacements in loaded "structures" were observed and measured. Stereo techniques have also been used to aid quantitative x-ray analysis of rough surfaces [4].

The introduction of automated matching techniques and microprocessor controlled, eucentric tilt stage will provide an operating environment for rapid development of stereo techniques in the physical sciences. Such a system would lend itself to evaluation of surface roughness for mechanical components such as seals, gears and bearings.

Other applications would include mapping of soft surfaces (e.g. coatings, magnetic tape), fractography and corrosion studies.

IV. PROOF-OF-CONCEPT EXPERIMENTS

Two experiments were carried out to evaluate the stereo pairs measuring technique. The first experiment was designed to measure the height of an electropolished step in a sample of M-50 tool steel. Once assured the technique would provide reasonable data, a second experiment was carried out on a specially prepared aluminum SEM stub. Details of instrument calibration and measurement procedures are provided in Appendix B.

IV.1 Description of the Specimens

Both specimens are displayed in Figure 1. The M-50 tool steel block (right) was electropolished for several seconds to manufacture a 5 μm depression. As noted, this was a sufficiently well defined topography for the first experiment.

The aluminum SEM stub (left) was also electropolished yielding an approximately 10 μm step. In addition, a rectangular grid was imposed by using the stylus set-up illustrated in Figure 2. The scratches 1, 2 and 3 spaced at 0.005 in. provided reference lines for the three profiles 4, 5 and 6. This sample allowed a one-on-one comparison between the stereo pair and stylus measurements.

IV. 2 Calibration of the Profilometer and SEM

The profilometer (stylus) instrument used for the experiments was a Talysurf IV. This is a standard surface metrology tool so that its use will not be described here. The stylus calibration was done using a 10 μm step created from JO blocks. The results are illustrated in Figure 3.

The microscope was checked for magnification and stage tilt angle. SEM magnification checks were provided by a gold grid with known hole spacings (Figure 4). Stereo micrographs were all taken at a magnification of 503X, the average value indicated for the 500X setting by the calibration procedure as detailed in Tables 1 and 2.

The mathematical basis for the stereo pair mensuration procedure is illustrated in Figure 5. Deviation in surface heights between two physical points (e.g. A & B) manifest in a parallax shift (X_L-X_R) in images taken at two different orientations (γ_L and γ_R). At high magnification, the SEM is a parallel projection instrument so that the relative height as viewed from the left image plane is Z_L. In the stylus reference, the relative height transforms to Z_V.

Analysis of the equations used to determine asperity heights from stereo pair photographs indicates that the tilt angle and angular differences must be reproducible and known with a high degree of accuracy. Clearly, the conventional method of fixing

a tilt angle by a rotating dial on the SEM chamber door is inadequate for quantitative measurements.

An aluminum stop was manufactured to correct this problem. This stop was designed to yield stereo pairs at 30° and 40° tilt angles with an angular difference of 10° between pairs.

In order to measure the tilt angles it was necessary to remove the SEM stage from the chamber. This was done using the sine table and stylus arrangement shown schematically in Figure 6. Unfortunately, the stylus method utilized to measure tilt angles will not take into account any out of plane motion due to the SEM door hinges. The actual tilt angles were 31.469° and 40.485° with an angular difference of 9.016° between stereo pairs. Documentation of the various trials to arrive at these averages is given in Table 3. The estimated reproducibility of the system was ± 0.1° from the average tilt angle. This tilt angle was considered acceptable. The calibrated arrangement is shown in Figure 7.

Stylus traces from the M-50 sample are shown in Figure 8. The profile's lines (1) and (2), begin at the center of the electropolished depression and progress along mutually orthogonal radial lines up the step to the unpolished portion (top) of the specimen. The maximum step heights along directions (1) and (2) are 5.8 μm and 5.6 μm, respectively. These vary depending on the selected points (X values) and the observed range in step heights is 4.6 μm to 5.8 μm.

Stereo micrographs for the M-50 specimen are displayed in Figure 9. Step heights were measured between various points below and above the "ridge" (bright region in center of micrographs) and perpendicular to the tilt axis. As indicated by Table 4, these values ranged from 4.38 μm to 5.81 μm with an average of 5.3 μm. These results demonstrated that the technique employed to make the stereo pair was proper and the method provided reasonable height data.

A similar procedure was carried out for the aluminum SEM stub sample. Stereo micrographs of a portion of this specimen are shown in Figure 10. At 500X only scratch lines 2 and 3, at the bottom and top of the "ridge", are visible. Therefore, pairs measurement of the step heights were taken between scratch lines 2 and 3 along trace lines 4, 5, and 6.

The stylus traces are displayed in Figure 11. Measurements were made from the bottom of scratch 2, clearly indicated by a sharp spike in each trace, to the bottom of scratch 3. The results are listed in Table 5, and demonstrate that the pair measurements are less than ten percent in error compared to the stylus results. As such, the procedure is quite reliable, at least for surface measurement on the order of 1 μm.

V. NECESSARY DEVELOPMENT/APPLICATION EFFORT

A fundamental goal in developing a microscale surface measurement capability is to enable a point by point 3-D representation of the surface. The data defining the surface should be available for manipulation as required by the specific objectives of a particular application. Development of the surface measurement capability described above requires:

1) Correlation and photogrammetric relocation software to match physical points between the two images and compute heights, respectively. The existence of software successfully employed to handle the central projection problem encountered with stereo matching of aerial photographs has been noted in Section III.3.3.

2) Hardware configuration compatible with timely data processing and useful output. A system for providing a 3-D surface measurement capability is outlined below.

The 3-D surface measurement system will consist of a SEM with a computer controlled scan generator and the hardware to digitize the SEM video signal. To digitize a stereo pair of SEM images, the specimen to be characterized is oriented in the initial position and the computer is used to scan the specimen and to digitize and store the first image. The specimen is reoriented (tilted, translated or combination) in the second position and the second image is digitized and stored. Scan software is employed to coordinate the sampling of the SEM video signal with the scan generator signal. The digitized stereo pair of images are then matched using correlation software. The matched pairs are analyzed further with photogrammetric relocation software to provide a 3-D map of the surface. The synthesis of the stereo matching and photogrammetric relocation techniques noted above with SEM and digital computing hardware enables the development of a new generation microscale surface measurement system capable of providing the point by point quantitative data required for an enhanced understanding of surface phenomena.

In addition to surface topography measurements, the system presents the following opportunities:

1) X-Ray Mapping

i) The system used in conjunction with the x-ray wavelength spectrometer may be used to semi-quantitatively determine concentrations of elements (boron through uranium) in a sample.

ii) The system could suppress noise in an x-ray elemental map. X-rays have a poor signal to noise ratio.

2) Backscattered Imaging Mode

The system could determine the percentage of light or heavey element inclusions from the contrast associated with the atomic number of the elements in the inclusion.

3) <u>Secondary Imaging Mode</u>

i) With appropriate steps the system could detect patterns on ceramic and metal fracture surfaces, for example, the system could be used to determine the percentage of transgranular or intergranular fracture in a specimen. It would also be possible to determine a reproducible average flaw size on ceramic flexure test samples.

ii) With pattern recognition capabilities, it would be possible to segregate inclusion types (lenticular, irregular, spherical) which would be useful in ceramic and metal research.

LIST OF REFERENCES - SECTIONS I & II

1. Gassel, S. S. and Pirvics, J., "Three Dimensional Microscale Topography System," SKF Report No. ALP78P020, December, 1978.

2. Thomas, T. R., "Recent Advances in the Measurement and Analysis of Surface Microgeometry," Wear, 33 (1975) 205-233.

3. Tallian, T. E., et al, "Rolling Bearing Damage Atlas, SKF Industries, Inc., (1974).

4. Williamson, J. B. P., "Microtopography of Surfaces," Proceedings of the Inst. of Mech. Engineers, 1967-1968, Vol. 182 Part 3K (21-30).

5. Guerrero, J. L. and Black, J. T., "Stylus Tracer Resolution and Surface Damage as Determined by Scanning Electron Microscopy," Trans. ASME, Journal of Engineering for Industry, November 1972, 1087-1092.

6. White, E. W., et al, "Computer Processing of SEM Images," Proceedings of the First Annual SEM Symposium, IIT Research Institute, Chicago, Illinois, 1968, 97-103.

7. Wells, O. C., Scanning Electron Microscopy, McGraw-Hill, Inc., (1974) 277-307. Chapter prepared by Allen Boyde.

8. Gassel, S. S., Project Status Report, "Three Dimensional Quantitative Microscale Topography System, Tasks I and II," November, 1979.

9. Boyde, A., "Practical Problems and Methods in 3-D Analysis of SEM Images," Scanning Electron Microscopy, 105-112, 1970.

10. Martin, M., et al, "A Tilt Calibration for Stereomicroscopy," Metallography, 9, 157-165, 1976.

11. Maune, D. F., "SEM Photogrammetric Calibration," Scanning Electron Microscopy, 207-216, 1975 Part 1.

12. Panton, D. J., et al, "Digital Cartographic Study and Benchmakr," Report AD-A064800, U.S.D.O.C., N.T.I.S., December 1978.

LIST OF REFERENCES - SECTION III

Section III.2

1. Greenwood, J. A., "Surface Measurements," Proc. Inst. of Mech. Engrs. 182 (Part 3G), 1-6, 1967-68.

2. Church, E. L., "Corrections to Stylus Measurement of Surface Finish," paper Th N1 presented at the Annual Meeting of the Optical Society of America, San Francisco 31 October - 3 November.

3. Radhakrishnan, V., "Effect of Stylus Radius on the Roughness Values Measured with Tracing Stylus Instruments," Wear 16, 325-335, 1970.

4. Radhakrishnan, V., "Does the Stylus Radius Affect Surface Roughness Measurements?", Tribology International, 101-103, April 1977.

5. Williamson, J. B. P., "Topography of Solid Surfaces," NASA Report SP-181, 85-142, 1967.

6. Williamson, J. B. P., "Microtopography of Surfaces," Proc. Inst. of Mech. Engrs. 182 (Part 3K), 21-30, 1967.

7. Richards, P. J., "Review of Methods of Measurement and Assessment of Surface Form and Texture," Proc. Inst. of Mech. Engrs. 182 (Part 3K), 453-465, 1967.

8. Green, E., "Review of Surface Texture Measurement and the Associated Metrological Problems." Proc. Inst. of Mech. Engrs. 182 (Part 36), 330-343, 1967-68.

9. Guerro, J. L. and Blank, J. T., "Stylus Tracer Resolution and Surface Damage as Determined by Scanning Electron Microscopy," J. of Engr. for Industry (ASME Trans.), 1087-1092, 1972.

10. Thomas, T. R. "Recent Advances in the Measurement and Analysis of Surface Microgeometry," Wear 33, 205-233, 1975.

11. Williamson, J. B. P. and Hunt, R. T., "Relocation Podfilometry," J. Phys., El, 749 (1968).

12. Edmonds, M. J., Jones, A. M., O'Callaghan, P. W., and Probert, S. D., "A Three-Dimensional Relocation Profilometer State," Wear 43, 329-340, 1977.

13. Williamson, J. B. P., Puller, J. and Hunt, R. T., "The Shape of Solid Surfaces," Surface Mechanics (ASME Publication), 24-35, 1969.

LIST OF REFERENCES - SECTION III (Continued)

Section III.2 (continued)

14. Young, R. D., "Surface Microtopography," Physics Today, November 1971, 42-49.

15. Tucker, R. C. Jr., and Meyerhoff, R. W., "An S.E.M. Study of Surface Roughness Measurements & Scanning Electron Microscopy," pp. 389-396, 1969.

16. Dupuy, O., "High-Precision Optical Profilometer for the Study of Micro-Geometrical Surface Defects," Proc. Inst. Mech. Engrs. 1967-1968, Vol. 182 PT3K.

17. Optical Profilometer, ANSA Technical Briefs, Fall, 1976.

18. Obraut, J. J., "Surface Measure Attains a New Level of Accuracy," Iron Age, August 1, 1977, pp. 156-158.

19. Trumpold, H., "Limits of Application of the Interference Methods for Surface Measurements," Proc. Instn. Mech. Engrs., 1967-68, Vol. 182, PT3K.

20. Sprague, R. A., "Surface Roughness Measurement Using White Light Speckle," Applied Optics, Vol. 11, No. 12, Dec. 1972.

21. Stover, J. C., "Roughness Characterization of Smooty Machined Surfaces by Light Scattering," Applied Optics, 14 (8), 1796-1802, 1975.

22. Church, E. L., Jenkinson, H. A., and Zavada, J. M., "Measurement of the Finish of Diamond Turned Metal Surfaces by Differential Light Scattering," Optical Engineering 16(4), 362-374, 1977.

23. Church, E. L., Jenkinson, H. A., and Zavada, J. M., "Relationship Between Surface Scattering and Microtopographic Features," Optical Engineering 1812, 125-136, 1979.

24. Church, E. L., "The Measurement of Surface Texture and Topography by Differential Light Scattering," Wear 57, 93-105, 1979.

25. Hildebrand, B. P., Gordon, R. L., and Allen, E. V., "Instrument for Measuring the Roughness of Supersmooth Surfaces," Applied Optics 13 (1), 177-180, 1974.

26. Church. E. L., "The Role of Surface Topography in X-Ray Scattering," Presented at the SPIE Imaging X-Ray Optics Workshop, 23-24 May, 1979.

27. Emslie, A. G., and Aronson, J. R., "Spectral Reflectance and Emittance of Particulate Materials. 1: Theory," Applied Optics 12 (11) 2563-2572 (1973).

LIST OF REFERENCES - SECTION III (Continued)

Section III.2 (Continued)

28. Aronson, J. R., and Emslie, A. G., "Spectral Reflectance and Emittance of Particulate Materials. 2: Applications and Results," Applied Optics 12 (11), 2573-2584, 1973.

29. Tanner, L. H., and Fahoum, M., "A Study of the Surface Parameters of Ground and Lapped Metal Surfaces, Using Specular and Diffuse Reflection of Laser Light," Wear, 36 (1976) 299-316.

30. "Supergage Checks Supersmooth Surfaces," Industry Week, P. 51, November 10, 1980.

31. Mikhail, E. M., "Hologrammetry: Concepts and Applications," Photogrammetric Engineering, 1407-1422, 1974.

32. Ribbens, W. B., "Surface Roughness Measurement by Two Wavelengths Holographic Interferometry," Applied Optics 13 (5) 1085-1088 1974.

33. "Holographic Characterization of Ceramics: Roszhart, T. V. and Bohn, J. R., Report No. AD-761 198 Prepared by TRW systems group for the Department of the Navy.

34. Brandis, Elmar K., "Comparison of Height and Depth Measurements with the SEM and TEM Using a Shadow Casting Technique," SEM Sym., April, 1972.

35. White, E. W. et al., "Quantitative SEM Characterization Methods for Ceramic Materials in All Process Stages and Applications to High Strength Aluminas and Silicon Nitride," Report No. AD-771 478.

36. Lebiedzik, J. and White, E. W., "Multiple Detector Method for Quantitative Determination of Microtopography in the SEM," Scanning Electron Microscopy 1973 (Part 1), 181-187.

37. Dancy, J. H. and Bennett, J. M., "Investigation of Electron Stereo-microscopy as a Method for Determining Heights of Features on Evaporated and Sputtered Films and on Polished Surfaces," High Energy Laser Mirrors and Windows, semi-annual reports No. 7 and 8 (NWC TP 5845), Naval Weapons Center California, July 1976, pp. 166-176.

38. Lebiedzik, J., "An Automatic Topographical Surface Reconstruction in the SEM," Scanning 2, 230-237 (1979).

39. Matsuno, Y., et al., "The Microtopography of the Grinding Wheel Surface with SEM," Annals of the CIRP, Vol. 24, 1, 1975.

40. Bomback, J. L., "Stereoscopic Techniques for Improved X-Ray Analysis of Rough SEM Specimens," Scanning Electron Microscopy (Part 1), 1973, pp. 97-104.

LIST OF REFERENCES - SECTION III (Continued)

Section III.2 (Continued)

41. Kato, Y., Fukuhara, S., and Komoda, T., "Stereoscope Observation and Three Dimensional Measurement for Scanning Electron Microscopy," Scanning Electron Microscopy 1977, (Vol. 1), pp. 41-48.

42. Eyre, T. S. and Dutta, K., "Some Applications of the Scanning Electron Microscope in Wear Studies," Lubrication Engineering, Vol. 31, 10, pp. 521-529.

43. Boyde, A. and Ross, H. F., "Photogrammetry and the SEM", Photogrammetrics Record 8, 1975, pp. 408-457.

44. Heidenreich, R. D. and Matheson, L. A.," Journal of Applied Physics, 15, 1944, pg. 423.

45. Wells, O. C., Brit. Journal Applied Physics, 11, 1960, pp. 199-201.

46. Lane, G. S., Journal of Sci. Instrum., Ser. 2, 2, 1969, pg. 565.

47. Cripps, J.B.F. and Sang, H., "Stereo Height Measurements in Scanning Electron Microscopy," Rev. Sci. Instr. 41, 1970, pp. 1825-1827.

48. Boyde, A., "Practical Problems and Methods in the Three-Dimensional Analysis of Scanning Electron Microscope Images," SEM, 1970, pp. 105-112.

49. Howell, P.G.T. and Boyde, A., "Comparison of Various Methods for Reducing Measurements from Stereo-Pair Scanning Electron Micrographs to Real 3-D Data," SEM, 1972, pp. 233-240.

50. Dinnis, A. R., "After Lens Deflection and It's Uses," SEM, 1971, pp. 41-48.

51. Boyde, A., "A Stereo-Plotting Device for SEM Micrographs; and a Real-Time 3-D System for the IBM," SEM, 1974, pp. 93-100.

52. Boyde, A., "Measurement of Specimen Height Difference and Beam Tilt Angle in Anaglyph Real-Time Stereo TV SEM Systems," SEM, 1975, pp. 189-198.

53. Boyde, A., The Perception and Measurement of Depth in the SEM," SEM, 1979, pp. 67-78.

LIST OF REFERENCES - SECTION III (Continued)

Section III.2

54. Goldstein, J. et al, Practical Scanning Electron Microscopy,

55. Boyde, A., "Photogrammetry of Stereo Pair SEM Images Using Separate Measurements from the Two Images," SEM, 1974, pp. 101-108.

56. Howell, P.G.T., "A Practical Method for the Correction of Distortions in SEM Photogrammetry," SEM, 1975, pp. 199-206.

57. Maune, D. F., "SEM Photogrammetric Calibration," SEM, 1975, pp. 207-216.

58. Boyde, A. and Powell, P.G.T., "Taking, Presenting and Treating Stereo Data from the SEM-II," SEM, 1977, pp. 571-579.

59. Pawley, J.B., "Design and Performance of Presently Available TV-Rate Stereo SEM Systems," SEm, 1978, Vol. 1, pp. 157-166.

60. Kato, Y., Fukuhara, S., Komoda, T., "Stereoscopic Observation and Three-Dimensional Measurement for Scanning Electron Microscopy," SEM, 1977, pp. 41-48.

61. Emlen, W. M., "Comparative Evaluation of Pocket Stereoscopes," Project 698DB, Griffis A.F.B., New York, August 1977.

62. Neubauer, G., and Schnitger, A., "A New Sterepscope for Stereoscopic Pictures of All Sizes," BEDO 3, Remy. Verlag, Munster, 1970, pp. 411-414.

63. Haanstra, H. B., "Stereophotography with the Electron Microscope," Philips Technical Review 27, 1966, pp. 231-237.

64. Chatfield, E. J., More, J., and Nielsen, V. H., "Stereoscopic Scanning Electron Microscope at T.V. Scan Rates," SEM/IITRI/1974, pp. 117-124.

65. Ne[illegible]ic, M., "Preparation of Stereo Slides from Electron Mic[illegible]ograph Stereo-Pairs," pp. 135-147 in M.A. Hayat ed., Principles and Techniques of SEM, Vol. 1, Van Nostrand Reinhold, New York, 1974.

66. Boyde, A., "A Single-Stage Carbon Replica Method and Some Related Techniques for the Analysis of the Electron Microscope Image," J. Roy. Microsc. Soc., 86, 1967, pp. 359-370.

LIST OF REFERENCES - SECTION III (Continued)

Section III.2 (Continued)

67. Martin, D. B., "A New Mirror Stereoscope with Optical Means of Measuring Parallax," Proc. of Int. Soc. Photogrammetry Commission VII, Paris, Sept. 1966.

68. Burkhardt, R., "Quantitative Electron Microscopy - Part 3. Determination of the Third Dimension of Objects by Sterecscopy," Photogrammetric Engineering 31, 1965, pp. 8C2-806

69. Boyde, A., "Height Measurements from Stereo-Pair Scanning Electron Micrographs," BEDO 1, Remy Verlag Munster, 1968, pp. 97-105.

70. Eick, J. D., Johnson, L. N., and McGivern, R. F., "Stereoscopic Measurements on the Microscale by Combining Scanning Electron Microscopy and Photogrammetry," pp. 89-110 in Close Range Photogrammetry, pubd. by American Society of Photogrammetry, Falls Church, VA 22046, U.S.A., 1971.

71. Wood, R., "The Modification of a Topographic Plotters and its Application in the Three Dimensional Plotting of Stereomicrographs," Photogrammetric Record 7, 1972, pp. 454-465.

72. Burkhardt, R. and Helmcke, J. G., "Der Elmigraph I, ein Photogrammetrics Auswertgerät mit Selbstkartier ng für elektronenmikroskopische Stereoaufnahmen," Proc. Int. Conf. Electron Microscopy, London, 1954, pp. 651-658.

73. Hobbie, D. and Zeiss, C., "The Zeiss G-2 Stereocord: A Simple Stereoplotter for Computer Supported Plotting," Photogrammetric Record, 8 (47), April 1976, pp. 563-582.

74. Hoover, R. A., "Measuring Surface Variations with the SEM Using Deposited Contamination Lines," J. Phys. E.: Science Instruments, 4, 1971, pp. 747-749.

75. Swift, J. A., "Measuring Surface Variations with the SEM Using Lines of Evaporated Metal," J. Phys. E.: Science Instruments, 9, 1976, pp. 803-804.

76. Hersener, J. and Ricker, T., "Fine Automatische Fokussieringseinrichtung for Rasterelektroneumikroskope," Beitrage zur Elektroneumikroskopischen Direktabbildung von Oberflachen, 5, 1972, pp. 337-387.

77. Holburn, D. M. and Smith K.C.A., "On-Line Topographic Analysis in the SEM," Scanning Electron Microscopy, 1979, II, pp. 47-52.

LIST OF REFERENCES - SECTION III (Continued)

Section III.3.1

1. Bernstein, R., "Digital Image Processing of Earth Observation Sensor Data," IBM J. Res. Develop., January 1976.

2. Billingsley, F. C., "Photo-reconaissance Applications of Computer Processing of Images," Proc. Two-Dimensional Digital Signal Processing Conference, IEEE Inc., 345 E. 47th Street, New York, New York, 10017, 1971.

3. Billingsley, F. C., "Digital Image Processing for Information Extraction," International Journal of Machine Perception of Patterns and Pictures, 1972, pp. 337-362.

4. White, E. W. et al, "Computer Processing of SEM Images," Symposium, Scanning Electron Microscope, IIT Research Inst., 1968, pp. 95-103.

5. McMillon, R. E., et al, "Computer Processing of Binary Maps of SEM Images," Proc. of Second Annual SEM Symposium IIT Research Inst., Chicago, IL 60616, April 1969.

6. Matson, W. et al, "Computer Processing of SEM Images by Contour Analyses," Pattern Recognition, Vol. 2, Perganon Press, 1970, pp. 303-312.

7. Wang, J., "Feature Extraction by Interactive Image Processing," Photogrammetric Engineering and Remote Sensing, Vol. 43, No. 12, December 1971, pp.1495-1501.

8. Fiori, C. E. et al, "Some Techniques of Signal Processing in Scanning Electron Microscopy," Proc. of Seventh Annual SEM Symposium, IIT Research Institute, Chicago, IL, April 1974, pp. 167-174.

9. Jones, A. V. and Smith, K.C.A., "Image Processing for Scanning Microscopists," Scanning Electron Microscopy, Vol. 1, 1978, pp. 13-26.

10. Simon, R., "Image Processing for Scanning Electron Microscopy," Scanning Electron Microscopy, 1969, pp. 445-457.

LIST OF REFERENCES - SECTION III (Continued)

Section III.3.1 (Continued)

11. Lewis, B. and Sakison, D. J., "Computer Enhancement of Scanning Electro Micrographs," IEEE Transactions on Circuits and Systems, Vol. CCS-22, No. 3, March 1975, pp. 267-278.

12. Newbury, D. E. and Joy, D. C., "Characteristics of SEM Signals and Techniques for Signal Processing," Scanning Electron Microscopy, Part I, April 1973, pp. 151-158.

13. Yew, N. C. and Pease, D. E., "Signal Storage and Enhancement Techniques for the SEM," Scanning Electron Microscopy, Part I, April 1974, pp. 191-198.

14. Smith, K.C.A., Unitt, B. M., Holburn, D. M. and Tec, W. J., "Gradient Image Processing Using An On-Line Digital Computer," SEM, Vol. I, 1977, pp. 49-56.

15. Erasmus, S. J., Holburn, D. M. and Smith, K.C.A., "On-Line Computation of Diffractograms for the Analysis of SEM Images," SEM, Vol. 3, 1980, pp. 273-279.

LIST OF REFERENCES - SECTION III (Continued)

Section III.3.2

1. Catto, C.J.D. and Smith, K.C.A., "A Storage-Display System for the Scanning Electron Microscope," SEM, 1972, pp. 41-48.

2. Paden, R. S., Tillet, P. I. and Upton, J. M., "New Display Techniques for the Scanning Electron Microscope," SEM, 1970, pp. 211-216.

3. "The Quantinet 720 Image Analyzer," IMANSCO, 40 Robert Pitt Drive, Monsey, NY 10952.

4. Herzag, R. F., Lewis, B. L, and Everhardt, T. E., "Computer Control and the Scanning Electron Microscope," SEM, 1974, pp. 175-182.

5. Lebiedzik, J., "Multiple Electron Detector Method for Quantitative Microtopographic Characterization in the SEM," Ph.D. Dissertation, Pa. State University, 1975.

6. Oron, M. and Gilbert, D., "Combined SEM-Minicomputer System for Digital Image Processing," SEM, 1976, pp. 121-128.

7. Jones, A. V. and Unitt, B. M., "Computers in Scanning Microscopy," SEM, Vol. I, 1980, pp. 113-124.

LIST OF REFERENCES - SECTION III (Continued)

Section III.3.3

1. DIMES, Computer Sciences Corporation.

2. COSMIC, 112 Barrow Hall, University of Georgia, Athens, GA, 30602

3. Frank and Shimkin, "A New Image Processing Software System for Structural Analysis and Contrast Enhancement," Ninth International Congress on Electron Microscopy, Toronto, Vol. 1, 1978.

4. Smith, P.R., "An Integrated Set of Computer Programs for Processing Electron Micrographs of Biological Structures," Ultramicroscopy 3, 1978, pp. 153-160.

5. Saxton, W. O., Pitt, T. J. and Horner, M., "Digital Image Processing: The SEMPER System," Ultramicroscopy 4, 1979, pp. 343-354.

6. White, E. W., McKinstry, H. A. and Diness, A., "Qnatitative Surface Finish Characterization by CESEMI," NBS Special Publication 348, 1970, pp. 309-316.

7. "Image Analysis System for Scanning Electron and Optical Microscopes," Bulletin 28, LeMont Scientific, State College, PA.

8. Crombie, M. A., Lem, P.G. and Hay, T. A., "Single Photo Analysis of Sampled Aerial Imagery," U.S. Army Engineer Topographic Laboratories, Research Note ETL-RN-74-10 (AD-A012-176)

9. Gambino, L. A. and Crombie, M. A., "Digital Mapping and Associated Digital Image Processing," USAETL.

10. Ackerman, D. L., Crombie, M. A. and Powers, M.A., "Image Correlation on a Parallel Processor,", USAETL Report ETL-0061 (AD-A030-036)

11. Crombie, M. A., "Stereo Analysis of a Specific Digital Model Sampled from Aerial Imagery," USAETL Report ETL-0072 (AD-A033-567)

12. Crombie, M. A., "Delta Pulse Code Modulation Compressor Relative to Stereo Image Matching," USAETL Report ETL-0157 (AD-A060-251)

13. Panton, D. J. et al, "Digital Cartographic Study and Benchmark," USAETL Report ETL-0168 (AD-A064-800)

LIST OF REFERENCES - SECTION III (Continued)

Section III.3.3 (Continued)

14. Abshier, J. O., "Image-Image Correlator Advanced Concepts," Rome Air Development Center (RADC), Report RADC-TR-75-226 (AD-A017-764).

15. Brumm, G. A. et al, "AS-11B-X Automated Stereomapper," RADC Report RADC-TR-76-100 (AD-A025-428)

16. Moore, Patricia (Ed.), Cartographic and Statistical Data Base and Mapping Software, Vol. 8, Harvard University, Laboratory for Computer Graphics and Spatial Analysis, Cambridge, MA, 1980.

17. Mapping Software and Cartographic Data Base, Vol.8, Harvard University, Laboratory for Computer Graphics and Spatial Analysis, Cambridge, MA, 1979.

18. McAdams, H. T., "Computer Mapping and Data Presentation," Cornell Aeronautical Laboratory, Inc., Technical Memorandum, No. VJ-2330-6-55, 1969.

19. LARSYS 3, Multispectral Data Analysis Program, Program Summary, COSMIC, University of Georgia, Athens, GA.

LIST OF REFERENCES - SECTION III (Continued)

Section III.4

1. Boyde, A., Jones, S. J. and Pawley, J. P., "Some Practical Applications of Real Time T.V. Speed Stereo SEM in Hard Tissue Research," SEM, Part III, 1974, pp. 109-116.

2. Matsuno, Y, Yamada, H., Harada,M., Kobayaski, A., The Microtopography of the Grinding Wheel Surface with SEM," Annuals of the CIRP, Vol. 24/1/1975, pp. 237-242.

3. Davidson, D. L., "The Observation and Measurement of Displacements and Strain by Stereoimaging," SEM, Part II, 1979, pp. 79-86.

4. Bomback, J. L., "Stereoscopic Techniques for Improved X-Ray Analysis of Rough SEM Specimens," SEM, Part I, 1973, pp. 97-103.

FIGURE 1

ELECTROPOLISHED ALUMINUM STUB AND M-50 SPECIMENS

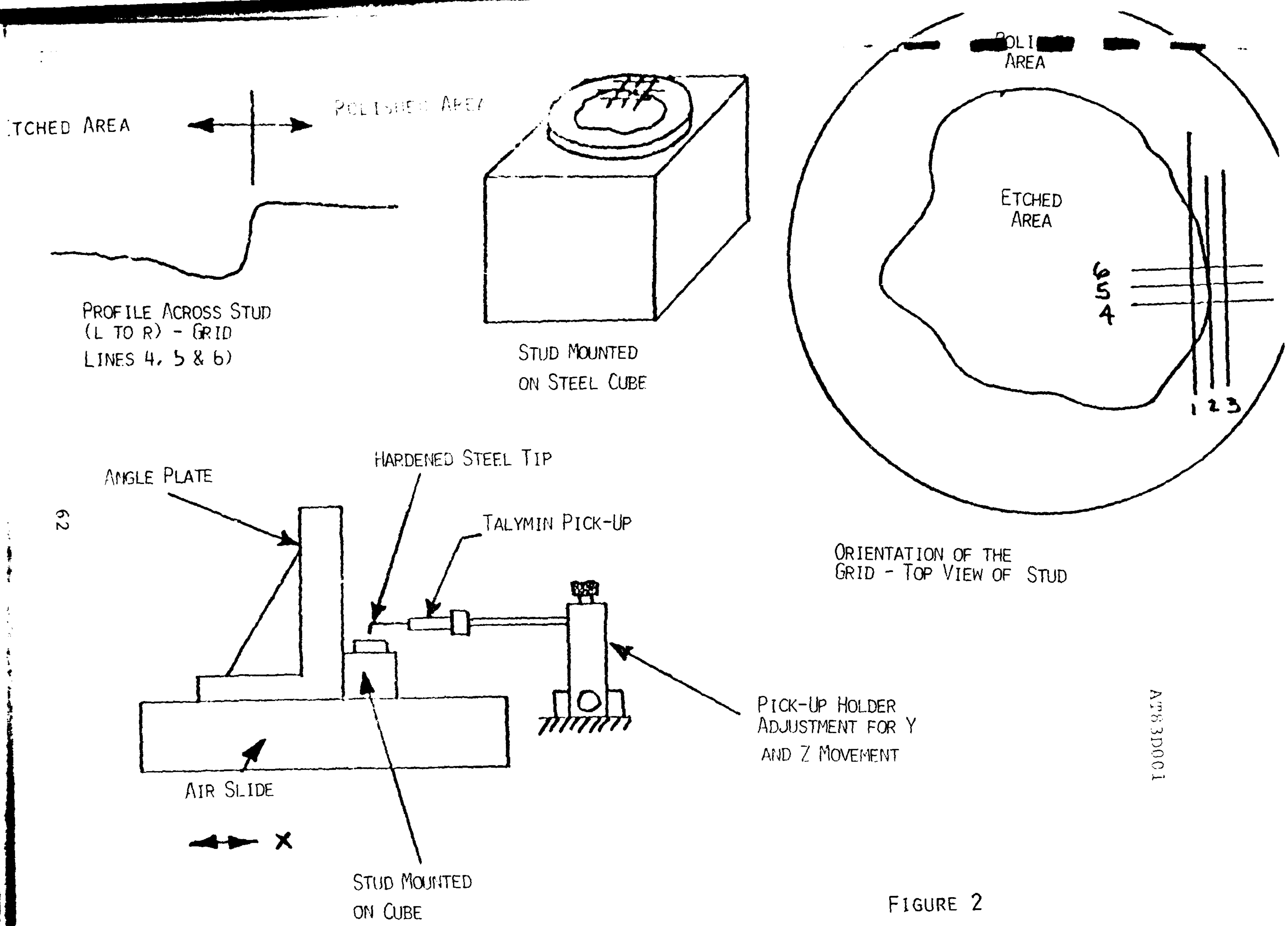


FIGURE 2

ORIENTATION

AT83D001

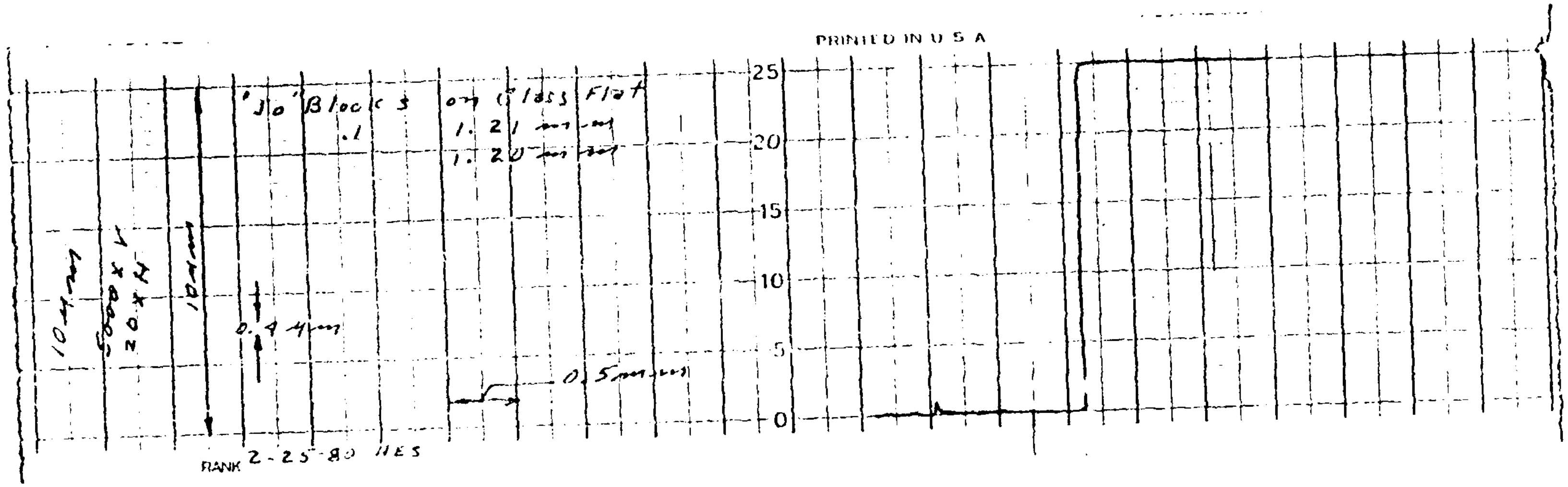
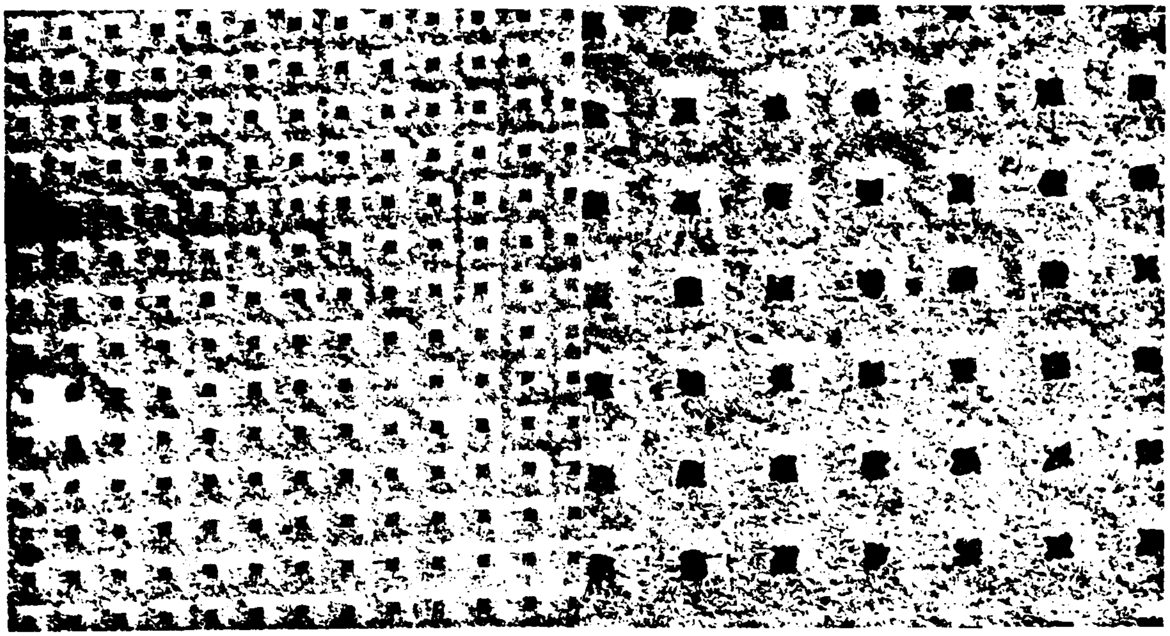


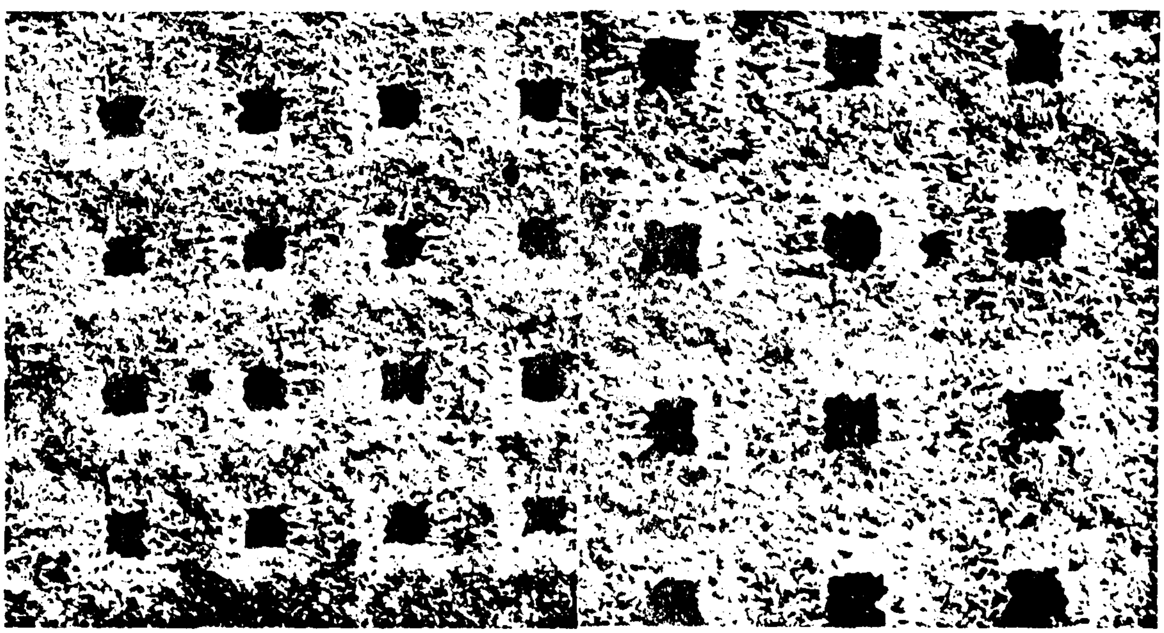
FIGURE 3

STYLUS CALIBRATION - 10 μm STEP USING JO BLOCKS

3D901



8484 250x 8485 500x

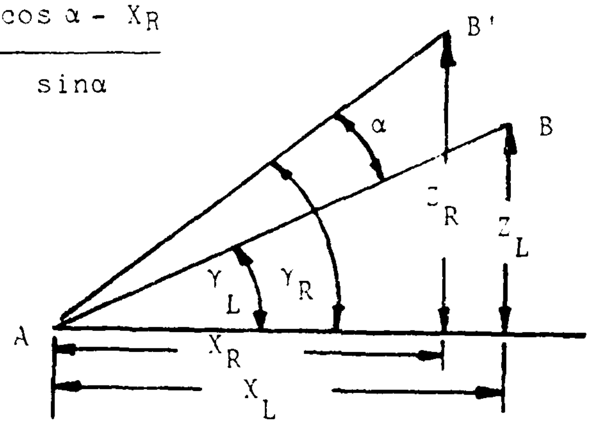


8486 750x 8487 1000x

FIGURE [illegible]

SEM PHOTOMICROGRAPH OF AU GRID AT VARIOUS MAGNIFICATIONS FOR SEM MAGNIFICATION CHECK

$$Z_L = \frac{X_L \cos\alpha - X_R}{\sin\alpha}$$



Parallel Projection Geometry

$$Z_V = (Z_L - X_L \tan\gamma_L)\cos\gamma_L$$

$$Z_{REAL} = Z_V/M$$

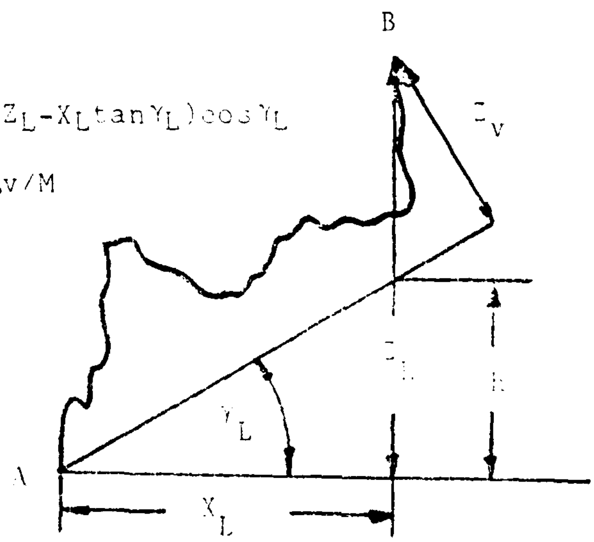
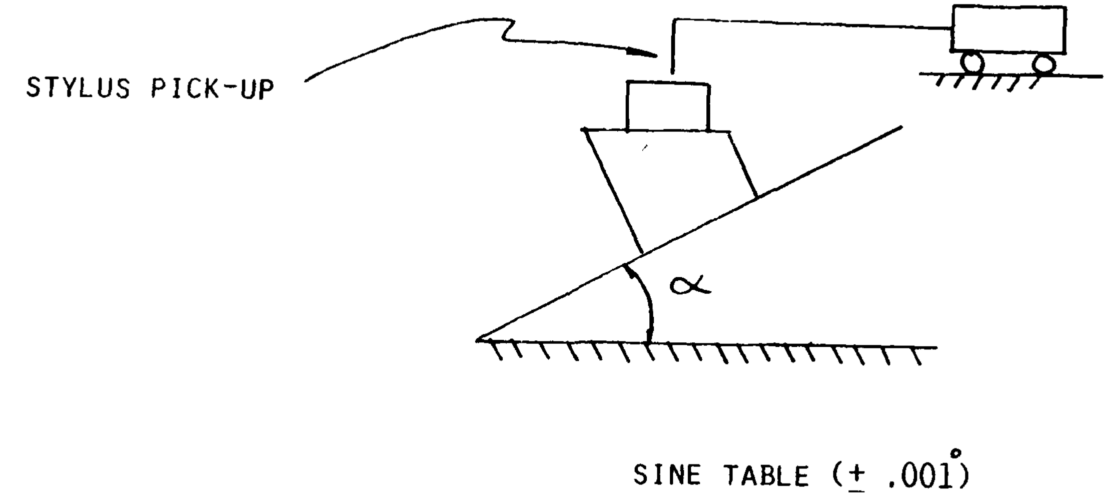


FIGURE 5

TRANSFORMATION OF RELATIVE HEIGHTS

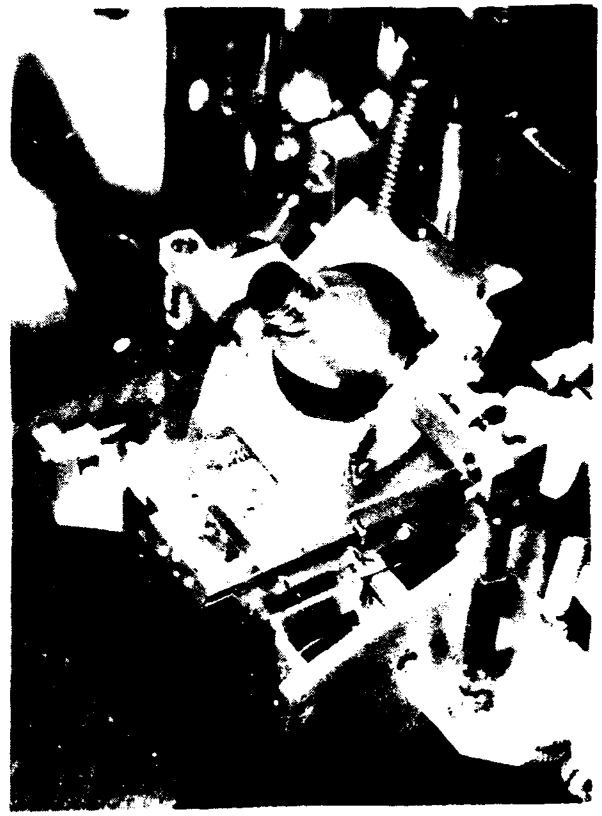
FIGURE 6

SCHEMATIC OF SET-UP FOR CALIBRATION OF TILT ANGLES



MEASURE DEVIATION (ANGULAR) OF TRACE FROM STRIGHT LINE 5 TIMES AND AVERAGE ($\bar{\Delta}$) - TILT ANGLE = $\alpha + \bar{\Delta}$

LEFT IMAGE SET-UP
31.469°



AT83D001

RIGHT IMAGE SET-UP
40.485°

FIGURE 7
CALIBRATED STOP-BLOCK ARRANGEMENT

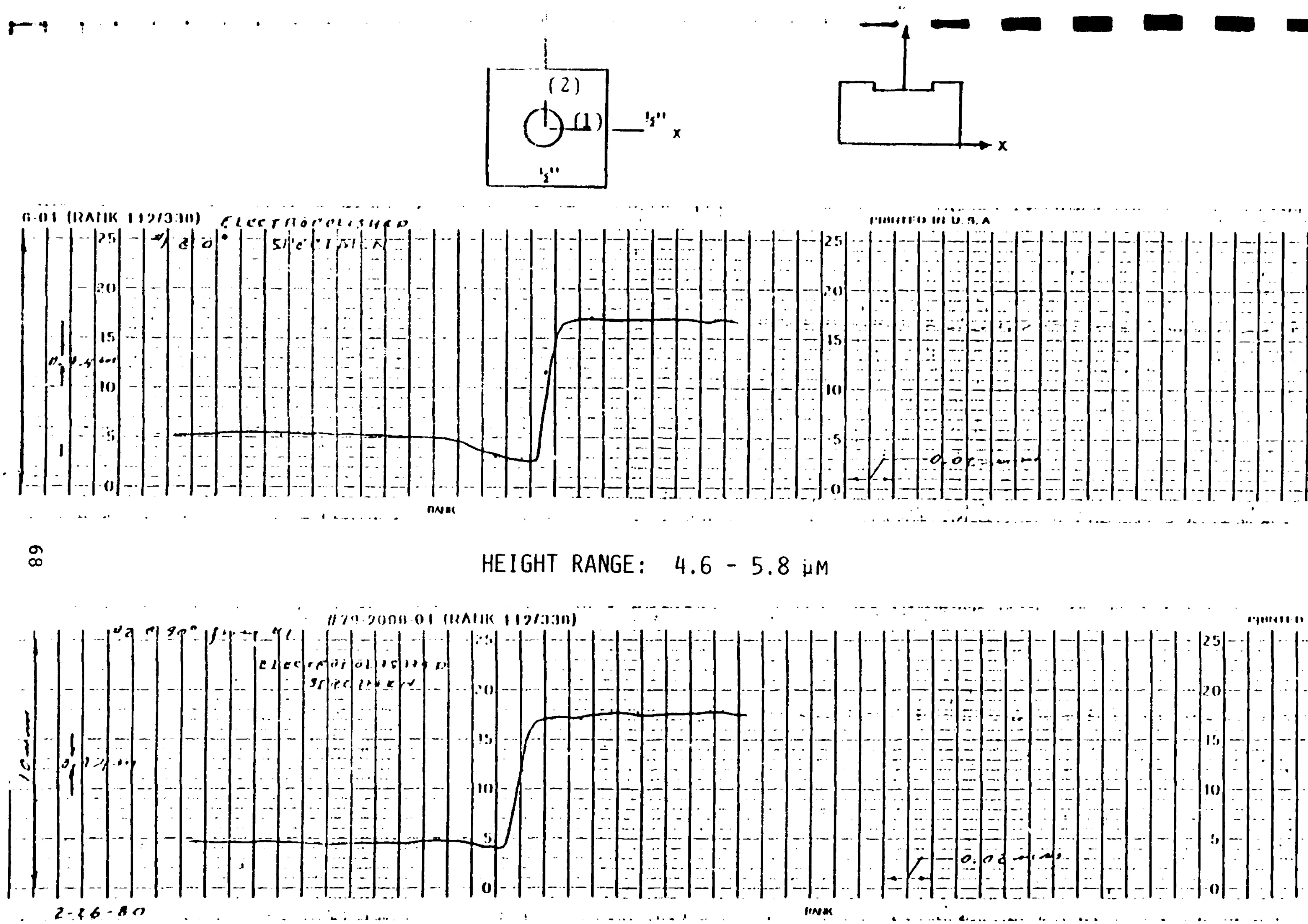
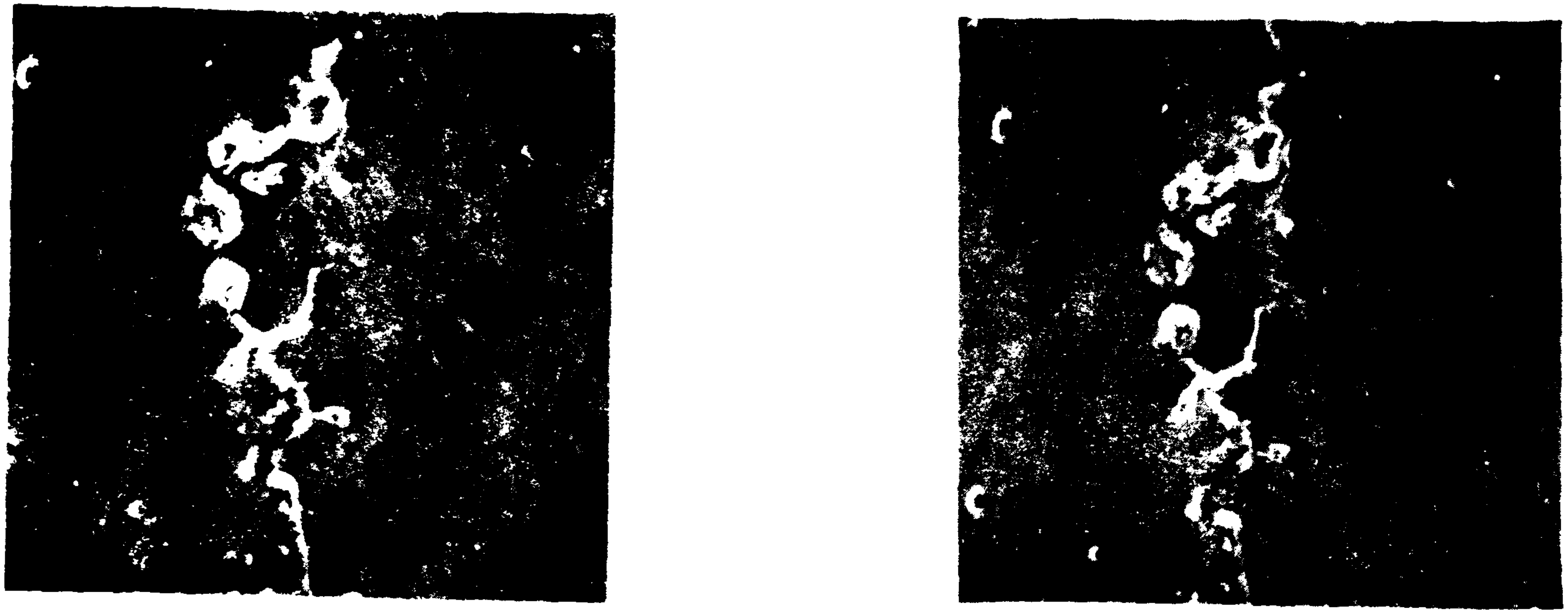


FIGURE 8
TRACES OF STANDARD STEP- DIRECTIONS 1 & 2

AT83D001

TILT AXIS

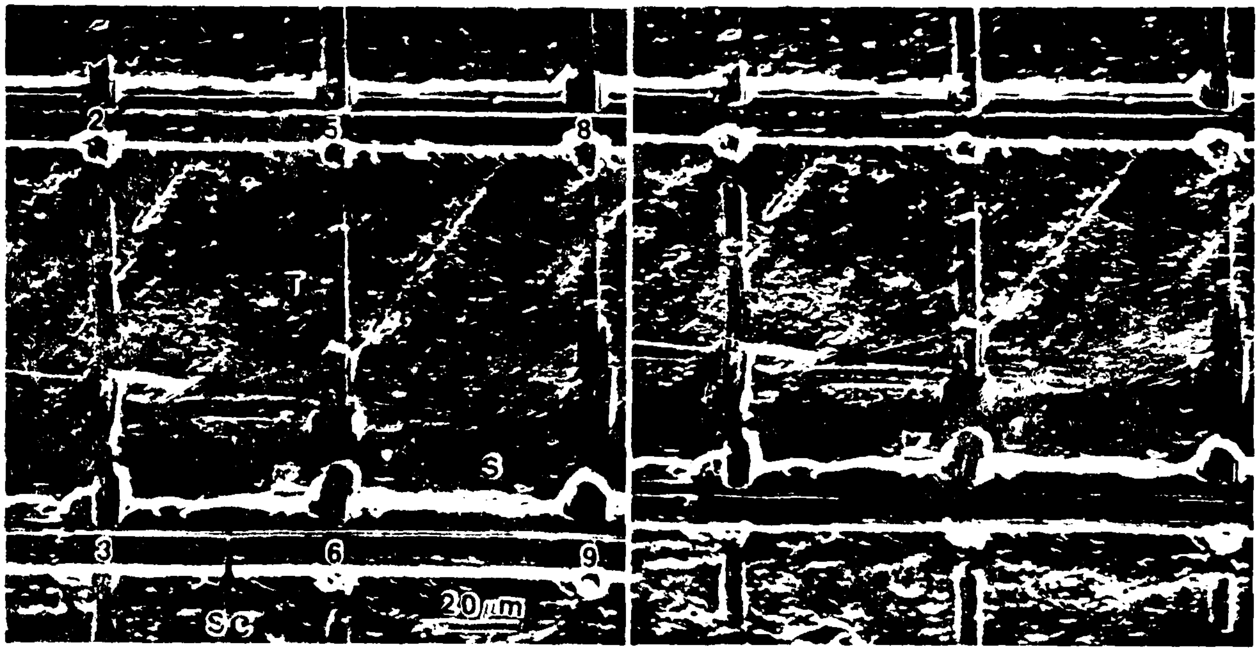


$\gamma_L = 39.47^\circ$ $\gamma_R = 40.49^\circ$

FIGURE 9

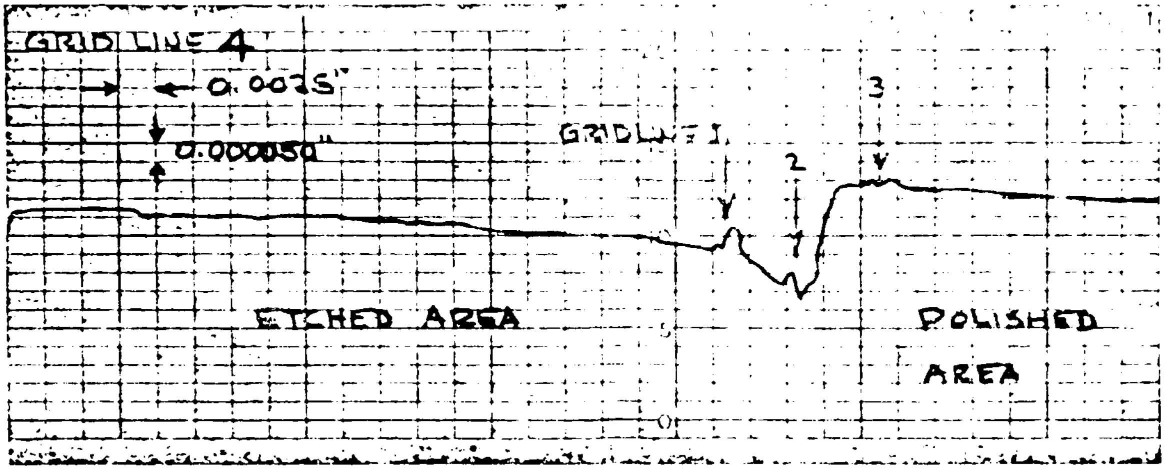
STEREO MICROGRAPHS OF M-50 SPECIMEN @ 500X

AT83D001

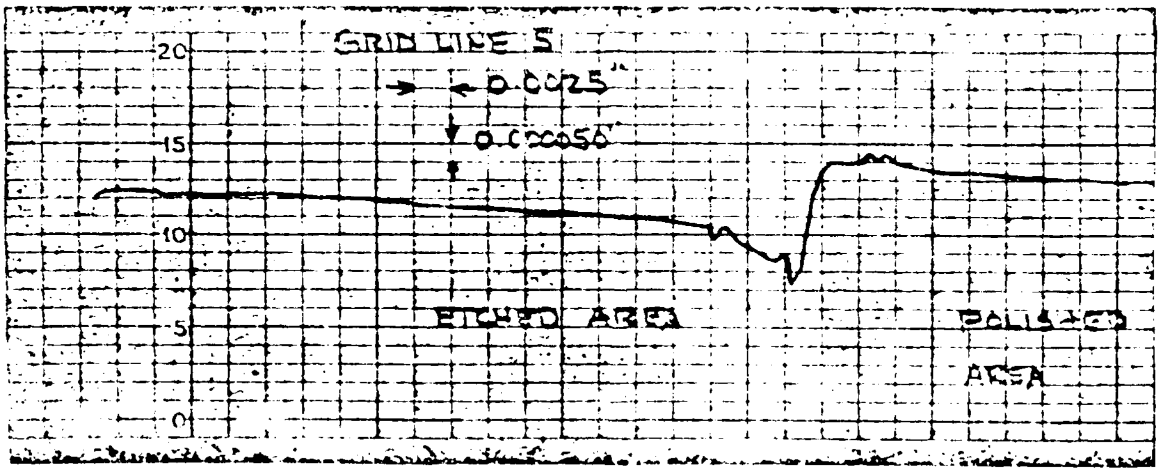


2
5
8
T
S
3
6
9
SC
20 μm

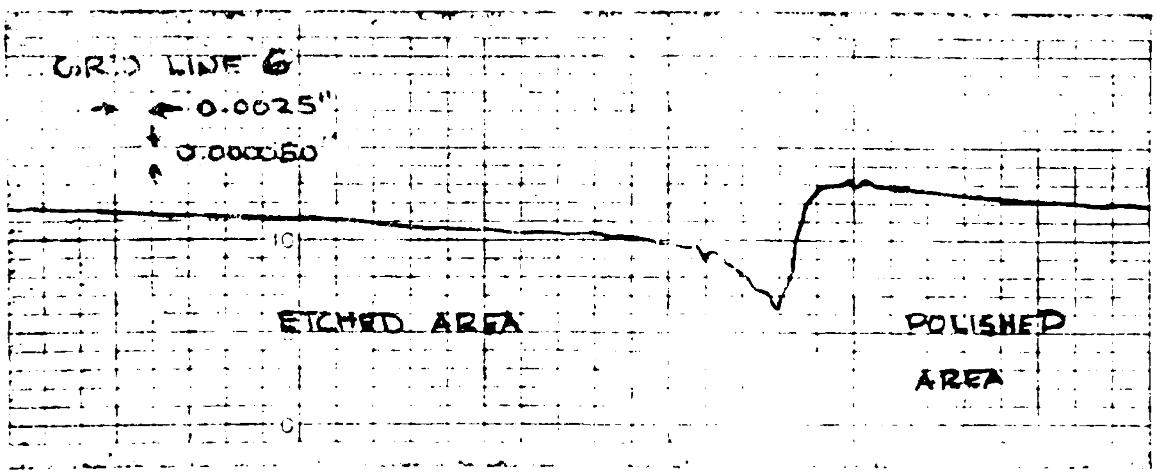
FIGURE 11



GRID LINE 4
0.0025"
0.000050"
GRIDLINE 1
2
3
0
ETCHED AREA
POLISHED
AREA



GRID LINE 5
20
0.0025"
0.000050"
15
10
5
0
ETCHED AREA
AREA



GRID LINE 6
0.0025"
0.000050"
10
0
ETCHED AREA
POLISHED
AREA

TABLE 1

Calculated Magnifications from Au Grid

	x - direction			y - direction		
Photo #	NT	$\overline{M}$	S.D.	NT	$\overline{M}$	S.D.
8484	5	253	0.45	5	253	0
8485	5	508	1.2	5	507	1.8
8486	4	775	2.36	5	777	4.1
8487	4	1009	6.3	3	1006	0

TABLE 2

Repeatability of Magnification at 500x

Photo #	Magnification
8485	507
----	500
----	506
----	500

$\overline{M} = 503$

S.D. = 3.8

NT = Number of measurements from photo

$\overline{M}$ = average magnification

S.D. = Standard deviation

TABLE 3

RESULTS OF TILT CALIBRATION

	TRIAL	DEVIATION (Δ)
INITIAL TILT	1	3′ 30″
	2	2′ 04″
$\alpha = 31^{\circ}\ 23'\ 56''$	3	5′ 51″
$\bar{\Delta} = 4'\ 18''$	4	4′ 28″
	5	5′ 38″
$\gamma_L = 31^{\circ}\ 28'14''$		
FINAL TILT	1	22′ 02″
	2	30′ 03″
	3	29′ 03″
$\alpha = 40^{\circ}\ 01'\ 05''$	4	29′ 04″
$\bar{\Delta} = 28'\ 03''$	5	30′ 03″
$\gamma_R = 40^{\circ}\ 29'\ 08''$		

TABLE 4

STEP HEIGHT MEASUREMENTS FROM STEREO PAIRS

Experimental Set-Up Conditions

Magnification = 508x

Initial Tilt (Left) = $31.47 \pm .04^{\circ}$

Final Tilt (Right) = $40.49 \pm .08^{\circ}$

Tilt Angle Difference = $9.02 \pm .12^{\circ}$

Point Set No.	Photo Set No.	X_L (in)	X_R (in)	Z_T (Height) (μm)
1	1	1.987	1.790	(4.85)
1	2	1.990	1.794	(5.21)
2	1	1.978	1.784	(5.39)
2	2	1.983	1.790	(5.81)
2	2*	1.980	1.787	(5.72)
3	1	2.925	2.628	(5.27)
4	1	1.600	1.447	(5.41)
5	1	3.188	2.864	(5.67)
6	1	2.913	2.614	(4.38)

Mean Value = $\bar{Z}_T$ = (5.30)

Standard Deviation = SD = (.45)

* Second Measurement

TABLE 5

MEASUREMENTS FROM STEREOPAIRS AND STYLUS OF ALUMINUM SEM STUB SPECIMEN

Data Points, Identified In Figure 2	% Error	Step Height: Stereopair Measurement	Step Height: Stylus Measurement
2 → 3	- 6.88	7.39 μm	7.94 μm
5 → 6	- 2.72	8.24 μm	8.47 μm
8 → 9	+ 9.61	9.47 μm	8.64 μm

APPENDIX A

State-of-the-Art of Stereomicroscopy

Computerized Literature Survey

State-of-the-Art of Stereomicroscopy

Computerized Literature Survey

Abstract

A literature search was undertaken to define the state-of-the-art of stereomicroscopy; quantitative surface topography on the microscale using SEM generated stereo pairs. Topically, this field includes: Analytic Photogrammetry, Scanning Electron Microscopy, Digital Image Processing and Automatic Pattern Recognition. The union of these sciences, provides the technological base for development of an automated 3-D SEM-Stereo Topography System, the long-range goal of this program.

This report details only the computerized literature search. Additional materials were acquired by hand searches and through personal communications with other researchers active in the field. Included is a description of the search strategies employed, quantification of results, as well as an evaluation of the various data bases surveyed.

Introduction

This report documents a comprehensive, computerized literature survey performed to define the state-of-the-existing art in stereomicroscopy. Other methods of literature collecting included library hand searches and personal communications. The results of the latter are not described here, but papers obtained in this way are included in the bibliography.

The survey was initiated at Drexel University. After filtering the available data bases, the following were chosen to be searched:

COMPENDEX	(Engineering Index)
DISS	(Dissertation Abstracts)
INSPEC	(Science Abstracts)
SSIE	(Smithsonian Science Information Exchange)
NTIS	(National Technical Information Service)

The remainder of the survey was conducted at General Electric, Valley Forge. The data bases selected were:

NASA	(National Aeronautics and Space Administration)
DDC	(Defense Department Command)

The subsequent sections describe the search methodology and results obtained. The relevant data for each search undertaken is quantified in Tables 1.1-1.9, 2.1-2.9, and clarified via several examples using the aforementioned Tables. The effort is then summarized, focusing on the value of the searches.

Description of Searches and Search Strategies

The search of each data base was initialized by inputting preselected keywords, words most likely to appear in titles or abstracts of relevant citations. The computer responds by assigning each keyword a numbered I.D. code, and printing the number of citations in the data base containing this keyword. The keyword Photogrammetry from Table 1.1 was input into data base INSPEC. The computer responded by assigning I.D. code "1" to the keyword and stating there are 85 citations in

this data base which have Photogrammetry in their Title or Abstract. Variable endings may also be used. For example, the next keyword input into the INSPEC data base was Scanning Electron Microscop-[e,y] (I.D. Code=2). The use of "-[e,y]" at the end of the keyword connotes a variable ending, and instructs the computer to search for both Scanning Electron Microscope and Scanning Electron Microscopy. The number of citations containing either of the two variations is then output (1243).

The above description applies to keywords in all data bases surveyed, which are listed in Tables 1.1 to 1.9. Note that authors names may be used as keywords (Tables 1.4; 1.9).

Keyword combinations are also assigned an I.D. code by the computer, and the number of citations which fit the combination is printed. Two logical connectors are used to form keyword combinations:

1) "and" - intersection of individual keyword citation sets (both keywords must be in citation)
2) "or" - union of individual keyword citation sets (either keyword must be in citation)

In Table 2.1, combination "1 and 2" is given an I.D. code of 3, and the data base holds 1 citation which contains both keyword #1 and keyword #2.

The sequence of events capsulized above are as follows:

1) The computer is told to search the data base for all citations containing both photogrammetry (1) and scanning electron microscop-[e,y] (2).

2) Computer labels input logic with an I.D. code (3).

3) Computer responds with number of citations (1) in the data base which meet the criteria.

The I.D. codes simplify the logical expressions (keyword combinations) by allowing the operator to input a representative keyword number (I.D. code) rather than retyping all desired keywords. This advantage becomes a necessity when large logical expressions are desired (see Table 2.9).

The keyword combinations used for each data base searched are listed in Tables 2.1 to 2.9.

Results

The citations considered relevant to the survey were printed, and are indicated by an asterisk (*) in Tables 1.1 to 1.9 and 2.1 to 2.9. The printed results from each data base surveyed are summarized in the following list:

1) INSPEC (Science Abstracts; Tables 1.1, 2.1) Ten citations were printed, and all ten were located via keyword combinations. The majority (9 of 10) deal with Image Processing.

2) COMPENDEX (Engineering Index; Tables 1.2, 2.2) Ten citations were printed, all dealing with Stereo Pairs. Keyword combinations in this data base proved fruitless.

3) NTIS (National Technical Information Service; Tables 1.3, 1.4, 2.3, 2.4) Two Separate searches were conducted in this

data base. The first search (Tables 1.3, 2.3) yielded twelve printed citations, eleven of which involve Stereo Pairs or Stereo Modelling. The second search (Tables 1.4, 2.4) produced two printed citations dealing with SEM, Photogrammetry and Image Processing.

4) SSIE (Smithsonian Science Information Exchange; Tables 1.5, 2.5)
Eleven citations from this data base were printed. Keyword combinations involving Photogrammetry, SEM and Image Processing produced the majority of references. Two citations containing Stereo Pairs were also printed.

5) DISS (Dissertation Abstracts; Tables 1.6, 1.7, 2.6, 2.7)
Two searches were conducted. The first search (Tables 1.6, 2.6) provided three printed citations, one each, dealing with Stereo Pairs, Height Measurement and Asperities, respectively. The second search (Tables 1.7, 2.7) proved fruitless.

6) NASA (National Aeronautics and Space Administration; Tables 1.8, 2.8)
Data relevant to all topics surveyed was found in this data base, which consists mainly of government sponsored research publications. In all, 390 citations were printed.

7) DDC (Defense Department Command; Tables 1.9, 2.9) SEM and Photogrammetry were the basis for the keyword combinations which provided most of the relevant citations printed (185) from this data base.

Summary and Conclusions

The methodology for implementing a computerized literature search to define the state-of-the-art of stereomicroscopy was described and the results obtained were presented.

Five data bases (COMPENDEX, DISS, INSPEC, SSIE, NTIS) surveyed at Drexel University provided minimal results. These searches yielded a total of 48 citations. Searches of the NASA and DDC data bases were the most fruitful, providing 575 citations, and indicating that the major portion of the work being done in this field is government sponsored.

SEARCH LOCATION: Drexel

VENDOR: BRS

DATA BASE: INSPEC (Science Abstracts)

TABLE 1.1 Keywords, I.D. Codes, and Number of Citations for Each Keyword

I.D. CODE	KEYWORD	NO. OF CITATIONS
1	Photogrammetry	85
2	Scanning Electron Microscop - [e,y]	1243
5	Image Processing	604

TABLE 2.1 Keyword Combinations, I.D. Codes and Number of Citations for Each Combination

I.D. CODE	KEYWORD COMBINATION	NO. OF CITATIONS
3	1 and 2	1*
6	5 and 2	5*
7	1 and 5	4*

* = Printed

SEARCH LOCATION: Drexel

VENDOR: Lockheed

DATA BASE: COMPENDEX (Engineering Index)

TABLE 1.2 Keywords, I.D. Codes and Number of Citations for Each Keyword

I.D. CODE	KEYWORD	NO. OF CITATIONS
1	Stereo Pairs	10*
2	Stereo Topography	0
3	Digitaliz - [e,ing,ed]	91
4	Height Measurement	54
5	Asperit - [y,ies]	291

TABLE 2.2 Keyword Combinations, I.D. Codes, and Number of Citations for Each Combination

I.D. CODE	KEYWORD COMBINATION	NO. OF CITATIONS
6	(1 or 2) and 3 and (4 or 5)	0
7	1 and (4 or 5)	0

* = Printed

SEARCH LOCATION: Drexel

VENDOR: BRS

DATA BASE: NTIS (National Technical Information Service)

TABLE 1.3 Keywords, I.D. Codes and Number of Citations for Each Keyword

I.D. CODE	KEYWORD	NO. OF CITATIONS
1	Electron Microscop - [e,y]	1199
2	Stereo Pairs	4*
3	Stereo Topography	0
6	Digitaliz - [e,ed,ing]	12
7	Height Measurement - [s]	25
8	Asperit - [y,ies]	17
13	Stereo Model - [s]	7*
16	Digitize - [d]	462

TABLE 2.3 Keyword Combinations, I.D. Codes and Number of Citations for Each Combination

I.D. CODE	KEYWORD COMBINATION	NO. OF CITATIONS
9	1 and 2 and (7 or 8)	0
10	1 and (7 or 8)	1*
11	1 and 2 and 6	0
12	2 and 6	0
17	1 and 2 and 16	0
18	(7 or 8) and 16	0

* = Printed

SEARCH LOCATION: Drexel

VENDOR: BRS

DATA BASE: NTIS (National Technical Information Service)

TABLE 1.4 Keywords, I.D. Codes and Number of Citations for Each Keyword

I.D. CODE	KEYWORD	NO. OF CITATIONS
1	Photogrammetry	180
3	Scanning Electron Microscop - [e,y]	542
5	Image Processing	292
10	Howell (author)	128

TABLE 2.4 Keyword Combinations, I.D. Codes and Number of Citations for Each Combination

I.D. CODE	KEYWORD COMBINATION	NO. OF CITATIONS
4	1 and 3	1*
6	5 and 3	1*
11	10 and 3	0

* = Printed

SEARCH LOCATION: Drexel

VENDOR: BRS

DATA BASE: SSIE (Smithsonian Science Information Exchange)

TABLE 1.5 Keywords, I.D. Codes and Number of Citations for Each Word

I.D. CODE	KEYWORD	NO. OF CITATIONS
1	Photogrammetry	36
2	Scanning Electron Microscop - [e,y]	751
4	Image Processing	203
8	Surface	10458
10	Surface Roughness	84
14	Stereo Pairs	2*
15	Stereometry	0
16	Cartography	11
17	Digital	1077

TABLE 2.5 Keyword Combinations, I.D. Codes and Number of Citations for Each Combination

I.D. CODE	KEYWORD COMBINATION	NO. OF CITATIONS
3	1 and 2	1*
18	16 and 17	2*
20	Mapping and 17	59
24	1 and 2 and 10 and 20	0
28	(1 or 2) and 10 and 20	0
29	1 or 2	786
30	29 and 4	3*
31	29 and 10	3*

* = Printed

SEARCH LOCATION: Drexel

VENDOR: BRS

DATA BASE: DISS (Dissertation Abstracts)

TABLE 1.6 Keywords, I.D. Codes and Number of Citations for Each Word

I.D. CODE	KEYWORD	NO. OF CITATIONS
1	Electron Microscop - [e,y]	454
2	Stereo Pair - [s]	1*
3	Stereo Model - [s]	0
4	Height Measurement - [s]	1*
5	Asperit - [y,ies]	1*
6	Digitize	17
7	Digitaliz - [e,ed,ing]	2
9	Metal Surface - [s]	67
11	Stereo Topography	0
14	Stereoscopic	25

TABLE 2.6 Keyword Combinations, I.D. Codes, and Number of Citations for Each Combination

I.D. CODE	KEYWORD COMBINATION	NO. OF CITATIONS
8	(6 or 7) and 1	0
10	9 and 1	0
15	1 and 14	0

* = Printed

SEARCH LOCATION: Drexel

VENDOR: BRS

DATA BASE: DISS (Dissertation Abstracts)

TABLE 1.7 Keywords, I.D. Codes and Number of Citations for Each Keyword

I.D. CODE	KEYWORD	NO. OF CITATIONS
1	Photogrammetry	16
2	Scanning Electron Microscop - [e,y]	41
4	Image Processing	39
7	Digital Processing	11
10	Computer Mapping	0

TABLE 2.7 Keyword Combinations, I.D. Codes, and Number of Citations for Each Combination

I.D. CODE	KEYWORD COMBINATION	NO. OF CITATIONS
3	1 and 2	0
5	4 and 2	0
6	1 and 4	0
8	1 and 7	0
9	2 and 7	0

SEARCH LOCATION: General Electric, Valley Forge

VENDOR: RECON

DATA BASE: NASA (National Aeronautics and Space Administration)

TABLE 1.8 Keywords, I.D. Codes and Number of Citations for Each Keyword

I.D. CODE	KEYWORD	NO. OF CITATIONS
1	Photogrammetry	1806
2	Aerial Photography	4718
4	Scanning Electron	1110
6	SEM	591
14	Surface Geometry	1599
15	Textures	542
16	Roughness	92
17	Surfaces	344
18	Topography	2507
21	Digital Techniques	3389
22	Imaging Techniques	6952
23	Imagery	1918
24	Photomicrography	664
27	Stereophotography	865
28	Stereoscopy	180
31	Image Processing	975
33	Digital Processing	415
42	Mapping	5198
43	Photomapping	1680
48	Mars Surface	1692
49	Lunar Topography	2484

AD-A137 871 DEVELOPMENT OF A 3-D MICROSCALE TOPOGRAPHY SYSTEM PHASE I(U) SKF TECHNOLOGY SERVICES KING OF PRUSSIA PA S S GASSEL ET AL. DEC 83 SKF-AT83D001 N00014-79-C-0792 2/2

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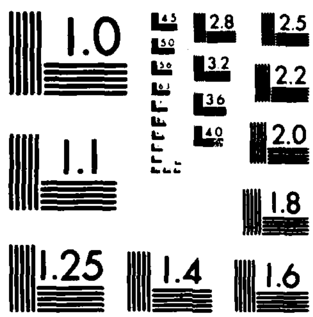


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

SEARCH LOCATION: General Electric, Valley Forge

VENDOR: RECON

DATA BASE: NASA (National Aeronautics and Space Administration)

TABLE 2.8 Keyword Combinations, I.D. Codes and Number of Citations for Each Combination

I.D. CODE	KEYWORD COMBINATION	NO. OF CITATIONS
3	1 or 2	5848
11	4 or 6	1458
12	1 and 2	676
13	3 and 11	5*
19	14 or 15 or 16 or 17 or 18	5054
20	11 and 19	26*
26	21 or 22 or 23 or 24	12476
30	26 or 27 or 28	1034
35	31 or 33	1159
36	30 and 3	1184
37	35 and 3 and 30	45*
38	30 and 11	74*
39	11 and 35	1*
40	19 and 3	427
41	40 and (30 or 35)	100*
44	42 or 43	6858
45	44 and 3	1447
46	44 and 11	2*
47	44 and 19 and (30 or 35)	115*
50	48 or 49	4138
51	(19 or 44) and 50	448
52	3 and 50	132
53	52 (from 1974 to present)	53
54	3 and 50 and (19 or 30)	49
55	54 (from 1974 to present)	22*

* = Printed

SEARCH LOCATION: General Electric, Valley Forge

VENDOR:

DATA BASE: DDC (Defense Department Command)

TABLE 1.9 Keywords and I.D. Codes

I.D. CODE	KEYWORD
1	SEM
2	Scanning Electron Microscop - [e,es,y]
3	Digital Imag - [e,es,ing]
4	Digital Map - [s, ping]
5	Digital Cartograph - [y,ic]
6	Digital Photogrammetry
7	Digital Correlation
8	Digital Techniques
9	Image Processing
10	Image Correlation
11	Image Restoration
12	Imaging Techniques
13	Surface Roughness
14	Roughness
15	Topography
16	Texture - [s]
17	Surface Analysis
18	Height Finding
19	Map Plotters
20	Map - [s,ping]
21	Cartography
22	Microphotography
23	Aerial Photography
24	Photogrammetry
25	Photomicrography
26	Stereoscopic map - [s,ping]
27	Stereoscopic display
28	Stereoscopic Cameras
29	Stereomapping
30	Stereophotography
31	Stereophotogrammetry
32	Electron Microscop - [e,es,y]
33	Digital Image Correlation
34	Digital Recording Systems
35	Surfaces
36	Surface Properties
37	Stereoscopic Display Systems
38	Stereoscopic Mapping Instruments
39	Stereoscopes
40	McAdams, H. T. (author)
41	Panton, D. J. (author)
42	Crombie, M. A. (author)

SEARCH LOCATION: General Electric, Valley Forge

VENDOR:

DATA BASE: DDC (Defense Department Command)

TABLE 2.9 Keyword Combinations and Number of Citations

KEYWORD COMBINATIONS	NO. OF CITATIONS
(1 or 2) and (3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12)	0
(1 or 2) and (22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30 or 31)	0
(1 or 2) and (13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21)	35*
29 and 37	301
(31 or 30 or 29 or 38 or 37 or 28) and (9 or 11 or 4 or 3 or 33 or 13 or 35)	41*
(23 or 24) and (13 or 14 or 15 or 16)	38*
(2 or 32) and (23 or 24)	0
(2 or 32) and (4 or 9 or 25)	6*
2 and (3 or 33 or 20 or 11 or 34 or 35 or 36 or 17 or 22 or 28 or 37 or 18 or 19)	37*
41	8*
40	6*
42	14*

* = Printed

APPENDIX B

Proof-of-Concept Test

LETTER REPORT

TO: S. S. Gassel

REPORT NO: AT80C034L

PROJECT CODE:

TITLE: SEM Stereopair Techniques

DATE: July 24, 1980

FROM: T. Yonushonis

REFERENCE: SKF Letter Report AT80C008L, SEM Magnification Check

COPIES TO:

INTRODUCTION

An ETEC scanning electron microscope was used to obtain stereopairs of electropolished M50 and aluminum samples. Electropolishing provided a step or ledge in the material which allowed comparison between SEM stereopair measurements and conventional diamond stylus traces of the same area. Initial stereopairs of an M50 sample indicated that precise location of the tilt axis, as well as accurate tilt angle and parallel measurements are required to obtain results comparable to a stylus trace.

EXPERIMENTAL PROCEDURE

Magnification Calibration

Calibration of the SEM magnification was required to obtain reproducible images which could be used to quantitatively define step heights or asperity heights in an unknown sample. The SEM magnification calibration procedure used was detailed in SKF report number AT80C008L, entitled "SEM Magnification Check." Basically, the calibration procedure relied on measurements obtained from photographs of a gold grid containing 1000 lines per inch. The gold grid was photographed at a 0^{o}tilt angle while the accelerating current, condensor current, focus controls, and magnification controls were fixed. Focusing was accomplished by repositioning the sample along the Z axis. Magnification repeatability at 500x using the outlined technique was within 1% of the calibrated magnification.

SEM Stereopair Measurements - M50 Step Standard - 4.5 μm Step

Obtaining quantitative data from SEM stereopairs was complicated by four major factors: (1) the angle between the plane containing the tilt axis and the detector plane was not known (2) exact positioning of the sample at a given tilt was not possible with existing equipment (3) accurate measurements of distances on photographs is required (4) the diamond stylus did not scratch the M50 surface (so that the trace direction could be identified). Due to

these difficulties, it was necessary to manufacture an aluminum stop which could assure repeatable tilt angles and a new step standard from a softer material.

Tilt Axis Calibration

Analysis of the equations used to determine asperity heights from stereopair photographs indicated that the tilt angle and angular differences must be reproducible and known with a high degree of accuracy. Initial stereopair photographs of the M50 step standard using the standard SEM tilt axis confirmed that a high degree of confidence in the tilt angle was necessary and the conventional method of fixing a tilt angle by a rotating dial on the SEM chamber door was inadequate for quantitative measurements. An aluminum stop was manufactured to correct this problem. This stop was designed to yield stereopairs at 30° and 40° tilt angles with an angular difference of 10° between pairs. In order to measure the tilt angles it was necessary to remove the SEM stage from the chamber. Unfortunately, the stylus method utilized to measure tilt angles will not take into account any out of plane motion due to the SEM door hinges. The actual tilt angles were 31.469° and 40.485° with an angular difference of 9.016° between stereopairs. The estimated reproducibility of the system was $\pm 0.1^{\circ}$ from the average tilt angle. This tilt angle was considered acceptable.

SEM Stereopair Measurement - Aluminum Step Standard - 8 μm Step

An electropolished aluminum SEM stub was used to eliminate some of the problems encountered with the M50 step standard. Scratches approximately 0.13 mm (0.005 in) apart were scribed parallel to the electropolished step shown in Figure 1. These scratches could be used to identify stylus position relative to the step location. As can be seen in Figure 1, the stylus traces deformed the aluminum surface. The stylus also had a tendency to skip portions of the surface. This tendency which was related to the radius.

The stereopair shown in Figure 1 was obtained using the procedures identified to assure proper image magnification and tilt axis. No attempt was made to align the stylus traces with the photo edge.

Figure 2 shows an improved stereopair obtained by aligning the sample with the edges of the photo. Table 1 contains the data obtained from measurements of the stereopairs and corresponding stylus measurements.* Initially, the scribed scratches and stylus traces were aligned with the edges of the cathode ray tube (CRT). Alignment was simplified by decreasing the CRT brightness and increasing the contrast. Then, the x-y stage micrometers were used to move the image in the x and y directions on the CRT tube. Sample rotation assisted in aligning the x and y stage movements parallel to the edges of the CRT tube. Further improvements in image position

* See Figure 3.

were obtained by rotating the electron beam raster pattern until the scribe and stylus marks on the sample coincided with x and y stage movements and the edge of the CRT. It should be noted that these adjustments were made at the final image magnification, 503x. After sample alignment, the image was focused at 5000x in the reduced area mode. Image magnification was decreased to 503x, brightness and contrast adjusted, and the final image recorded photographically. Orientation of significant topographic features were sketched onto the CRT screen prior to changing the tilt angle to 40.485°. The higher angle photograph was obtained by simply adjusting the x and y positions and focusing with the z axis. No further adjustment of the sample rotation or raster rotation was required.

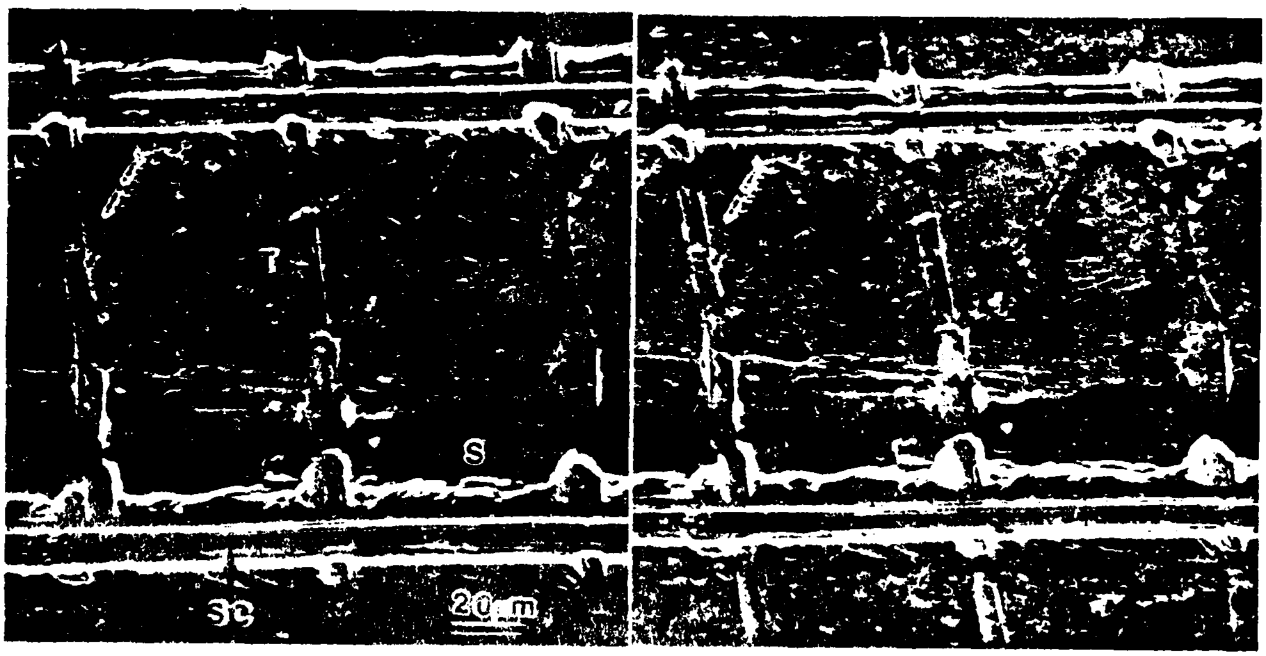
SUMMARY

The distance between planes produced by selective electro-polishing of aluminum was determined by measuring stereopair photomicrographs. These distances, approximately 8 μm, were within 10% of the value obtained from conventional stylus techniques.

Improvements in stereopair accuracy and production may be obtained by investigating new solid state backscattered electron detectors (provides higher contrast), SEM stages designed for stereopair work, and computer processing of picture points.

Tom Yonushonis
T. Yonushonis

Tilt Axis

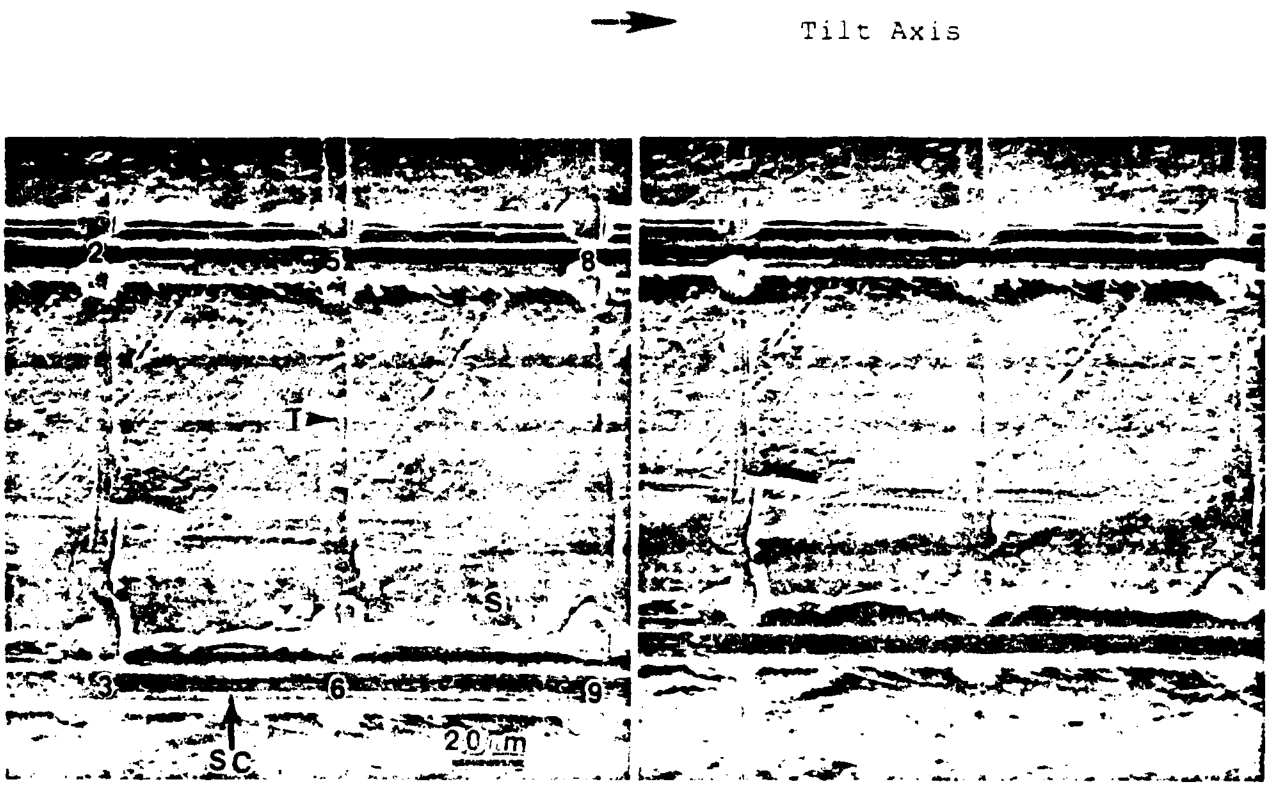


89 [illegible]

31.469° [illegible]

Figure 1. [illegible]
SEM [illegible]
scratches
S - [illegible]
T - [illegible]
SC - [illegible]

AT8...42

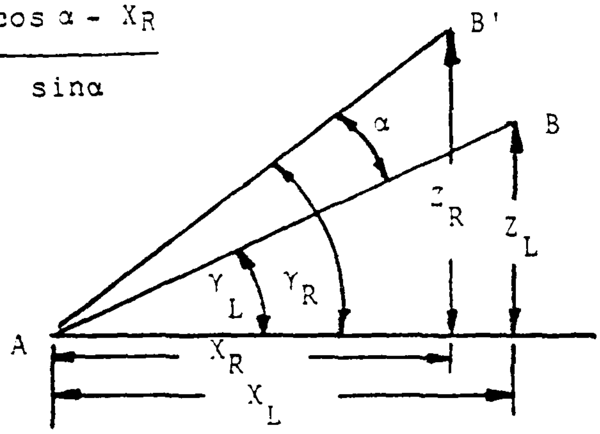


8981   8982   503x

31.469° Tilt   40.485° Tilt

Figure 2. Improved stereopair photographs of aluminum electropolished SEM stub with 8 μm step, stylus traces, and orientation scratches.
S - 8 μm step
T - stylus traces (three traces visible)
SC - scratches (two visible)

$$Z_L = \frac{X_L \cos\alpha - X_R}{\sin\alpha}$$



Parallel Projection Geometry

$$Z_V = (Z_L - X_L \tan\gamma_L)\cos\gamma_L$$

$$Z_{REAL} = Z_V/M$$

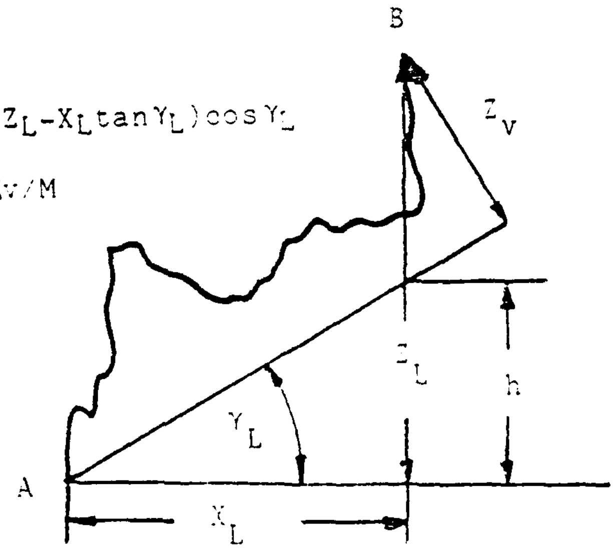


Figure 3. Transformation of Relative Heights

Table I

Measurements From Stereopairs and Stylus

Data Points, Identified In Figure 2	% Error	Step Height: Stereopair Measurement	Step Height: Stylus Measurement
2 → 3	- 6.88	7.39 μm	7.94 μm
5 → 6	- 2.72	8.24 μm	8 47 μm
8 → 9	+ 9.61	9.47 μm	64 μm

LETTER REPORT

TO: S. S. Gassel

REPORT NO: AT80C008L

PROJECT CODE: LC414

TITLE: SEM Magnification Check

DATE: February 1, 1980

FROM: T. Yonushonis

REFERENCE:

COPIES TO:

A gold grid containing 1000 lines per inch was used to check the SEM magnification at theoretical magnifications of 250x, 500x, 750x, and 1000x. The working distance was maintained constant at approximately 20 cm for a magnification multiplier of 1.25. This multiplier was chosen to allow necessary working distance clearance necessary for tilting specimens in the SEM chamber.

Table I contains the dial and guage setting used to obtain photographs of the Au grid. Focus was achieved by repositioning the specimen along the Z axis in order to avoid changing the magnification multiplier which is dependent on the settings of the focus controls.

Table II presents the SEM magnifications in the x and y plane of the image and the repeatability of the magnification studies. The results shown were encouraging since the magnifications were linear over the range studied and the magnifications were repeatable.

Figure 1 shows SEM photomicrographs of the Au grid at 250x, 500x, 750x, and 1000x.

Tony Yonushonis

T. Yonushonis

Table I

SEM Settings for Magnification Check

Accelerating Voltage	-	20KV	
Condenser Current	-	2.1 amps	
Condenser Setting	-	4.9 on dial indicator	
Focus Controls	-	Coarse	7.5
		Medium	5.0
		Fine	5.0
Tilt	-	0°	
Vernier Magnification Multiplier	-	1.0 for 250x, 500x, 1000x 1.5 for 750x	
Magnification Multiplier	-	1.25	

Table II

Calculated Magnifications from Au Grid

Photo #	x - direction NT	$\overline{M}$	S.D.	y - direction NT	$\overline{M}$	S.D.
8484	5	253	0.45	5	253	0
8485	5	508	1.2	5	507	1.8
8486	4	775	2.36	5	777	4.1
8487	4	1009	6.3	3	1006	0

Repeatability of Magnification at 500x

Photo #	Magnification
8485	507
----	500
----	506
----	500

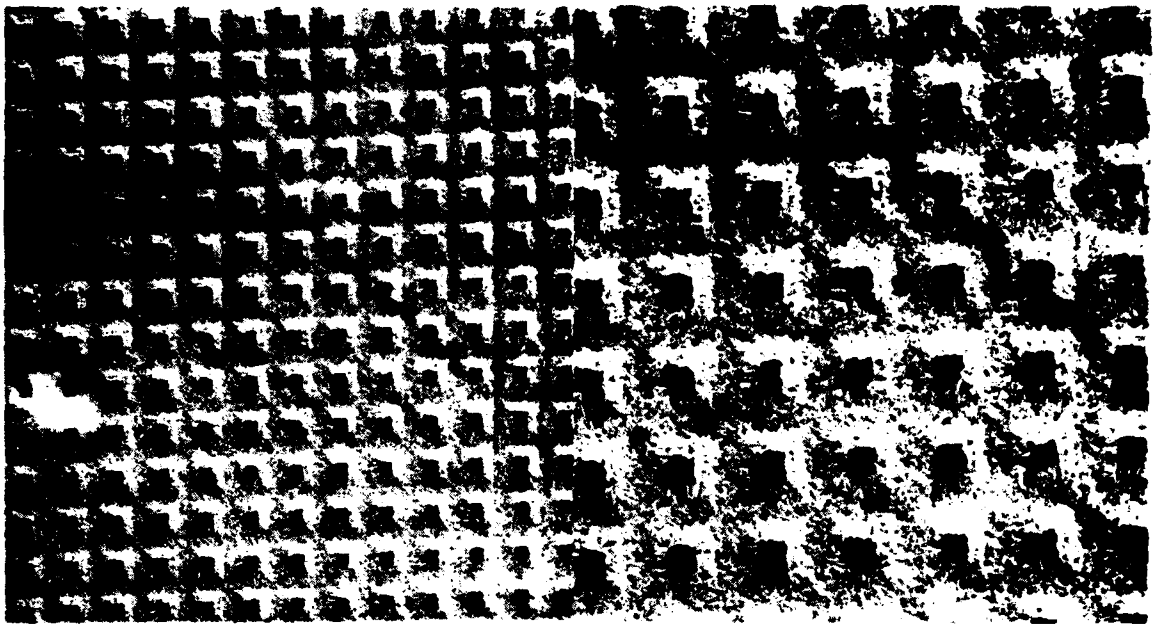
$\overline{M}$ = 503

S.D. = 3.8

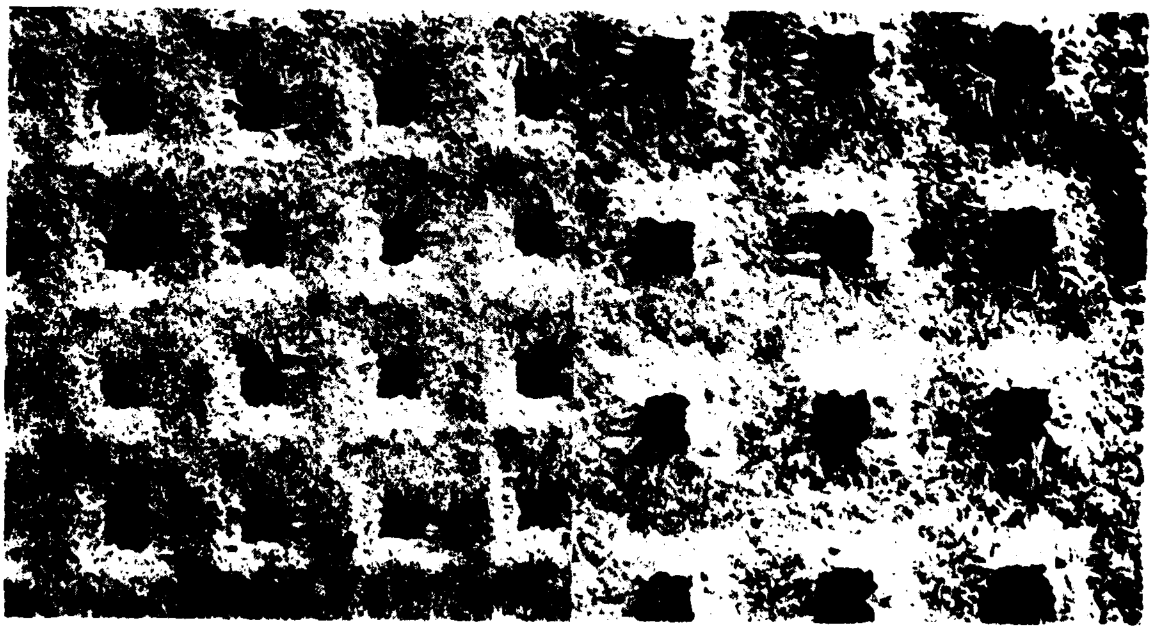
NT = Number of measurements from photo

$\overline{M}$ = average magnification

S.D. = Standard deviation



8484 250x 8485 500x



8486 750x 8487 1000x

Figure 1 SEM photo-micrograph of Au grid at various magnifications for SEM magnification check.

METROLOGY RESULT REPORT

To: S. S. Gassel

Metrology File No. 30-159

Metrology Reg. No.: 207

Project Code: LC414F1

Your S.R. No.: 220249

Date: 6/27/80

Title: CREATION OF GRID FOR ONR-SEM WORK

From: W.L. RHOADS

Copies to: F.R. MORRISON
P.S. GIVEN (P.1&2 ONLY)

• Data Requested: ON A POLISHED SOFT ALUMINUM STUD WITH AN ETCHED AREA IN THE CENTER, SCRIBE THREE LINES APPROXIMATELY 0.003" APART - ONE THROUGH THE ETCHED AREA, ONE THROUGH THE POLISHED AREA, AND ONE THROUGH THE BOUNDARY BETWEEN THE AREAS. PERPENDICULAR TO THESE LINES TRACE THE PROFILE ACROSS THEM IN THREE LOCATIONS APPROXIMATELY 0.003" APART. THESE TRACES SHOULD ALSO YIELD A VISIBLE SCRATCH, ALTHOUGH NOT AS DEEP AS THE OTHERS.

• Figures:

FIGURE 1 SHOWS THE STUD AND THE ORIENTATION OF THE VARIOUS LINES

FIGURE 2 SHOWS THE THREE PROFILE TRACES

• Comments: ALL LINES WERE MADE WITH A HARDENED STEEL TIP HAVING AN END RADIUS OF APPROXIMATELY 0.001". THIS WAS MOUNTED IN A TAYLOR-HOBSON 112/1028 TALYMIN 4 PICK-UP. THE STUD WAS MOUNTED ON A STEEL CUBE WHOSE FACES WERE UTILIZED TO GET THE GRID LINES PERPENDICULAR TO EACH OTHER. THE CUBE WAS THEN MOUNTED ON THE TABLE OF THE LINEAR AIR SLIDE (AGAINST THE ANGLE PLATE) WHICH WAS USED TO TRAVERSE THE STUD. SPACING OF THE LINES WAS DONE BY USING THE HORIZONTAL MICROMETER FEED ON THE PICK-UP HOLDER. LINES 1-3 WERE MADE WITH THE PICK-UP ADJUSTED FOR IT'S HIGHEST TRACING PRESSURE AND THE VERTICAL PICK-UP FEED MOVED

PAGE 2

DOWN 0.020" PAST THE POINT WHERE THE TAYLOR-HOBSON RECTILINEAR RECORDER PEN MOVED OFF THE PAPER. THE CUBE WAS ROTATED 90° AND LINES 1-3 WERE TRACED AT THE HIGHEST PICK-UP PRESSURE WITH THE PEN AT APPROXIMATELY MID-SCALE IN ORDER TO GIVE A CLEARLY VISIBLE SCRATCH. THIS PRESSURE IS HIGHER THAN WOULD BE USED FOR NORMAL TRACING AND MUCH HIGHER THAN WOULD BE USED ON ALUMINUM. NOTE THAT WITH THE SOFT ALUMINUM ANY PROFILE TRACE WOULD CUT THE FURROWS OF LINES 1-3 AND THUS NOT GIVE A TRUE PICTURE OF THE GEOMETRY. ALSO NOTE THAT THE RADIUS OF THE PICK-UP TIP USED ON THE TALY-SURF SURFACE ROUGHNESS EQUIPMENT HAS A MAXIMUM RADIUS OF 0.00005" (1/20 THAT OF THE TIP USED HERE, WHICH IS MUCH SHARPER THAN NORMALLY USED FOR PROFILE TRACES).

Wm J Rhoads

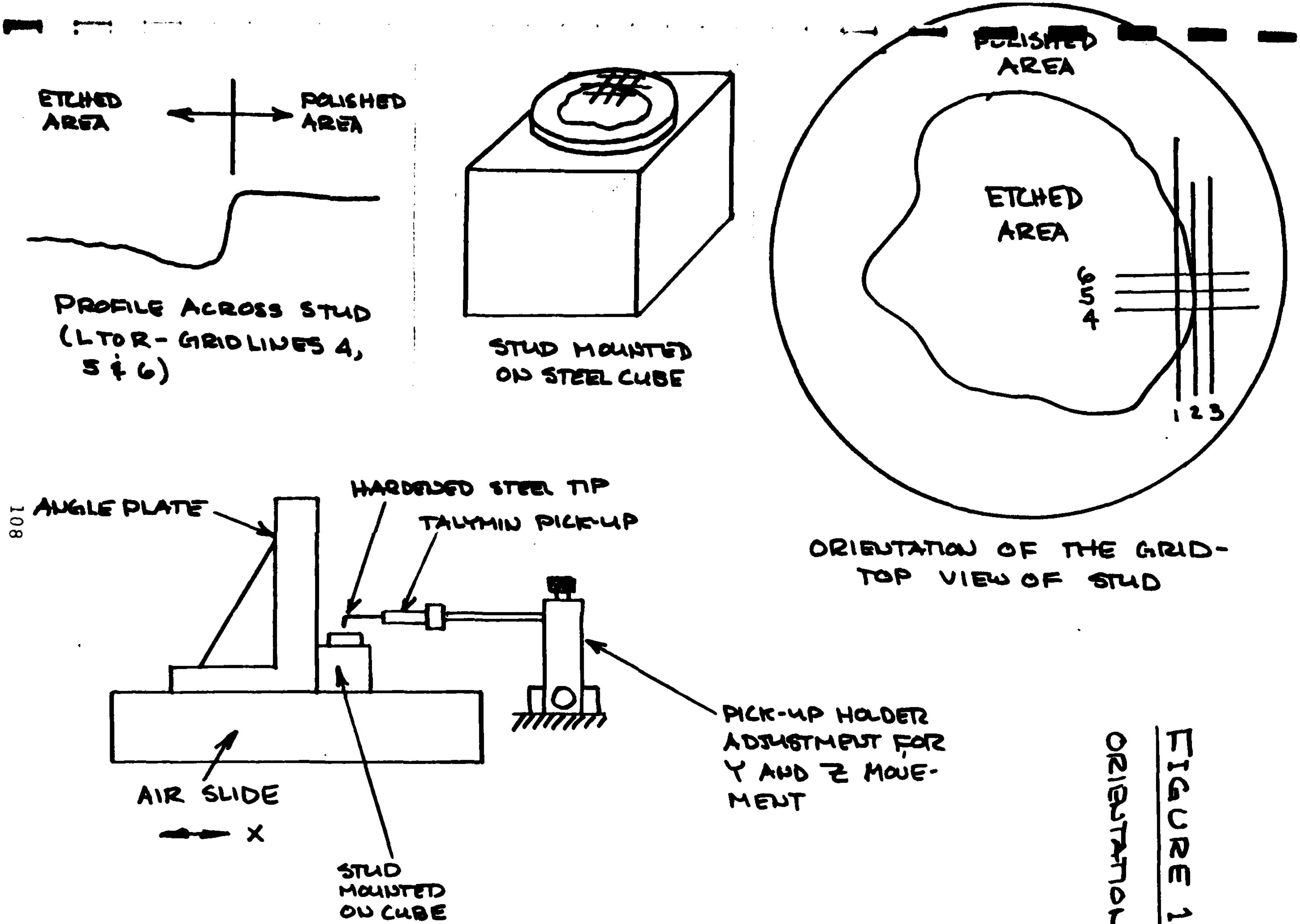
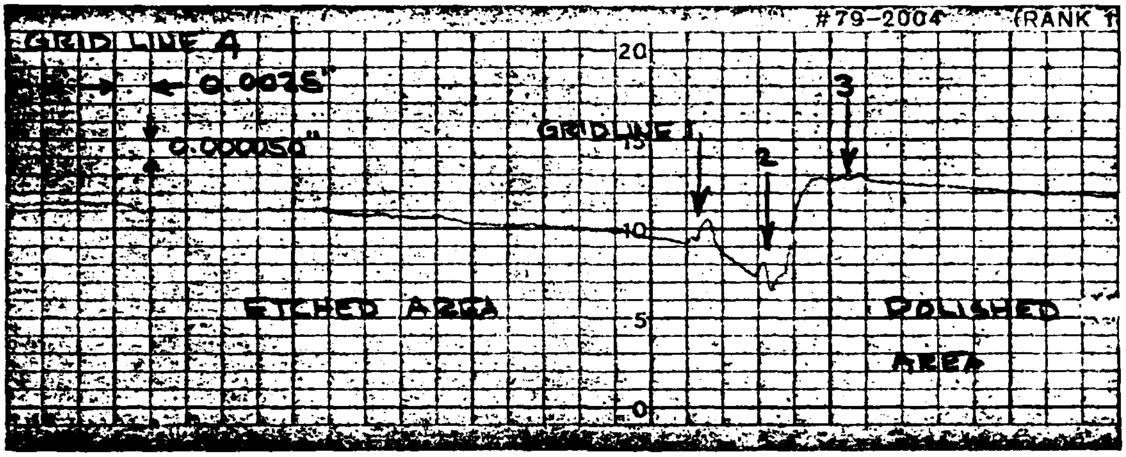
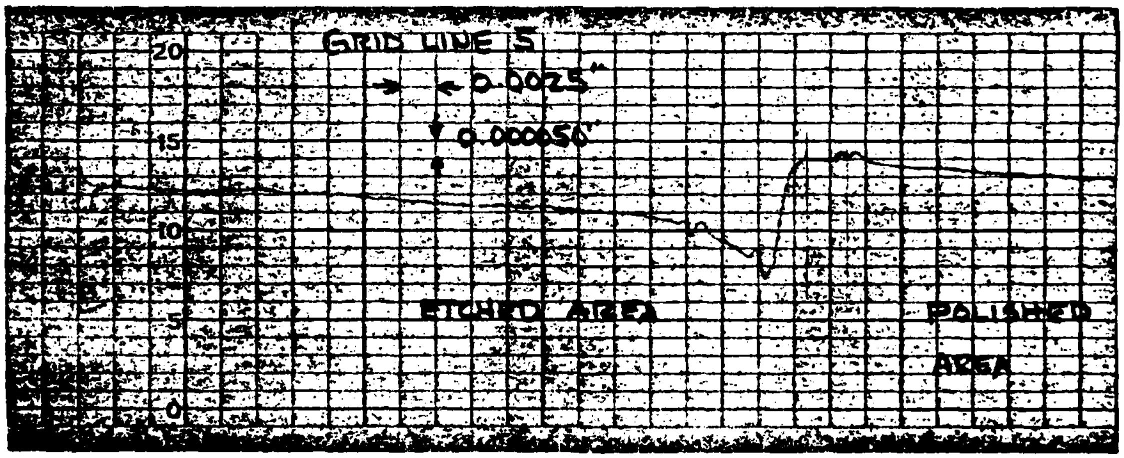


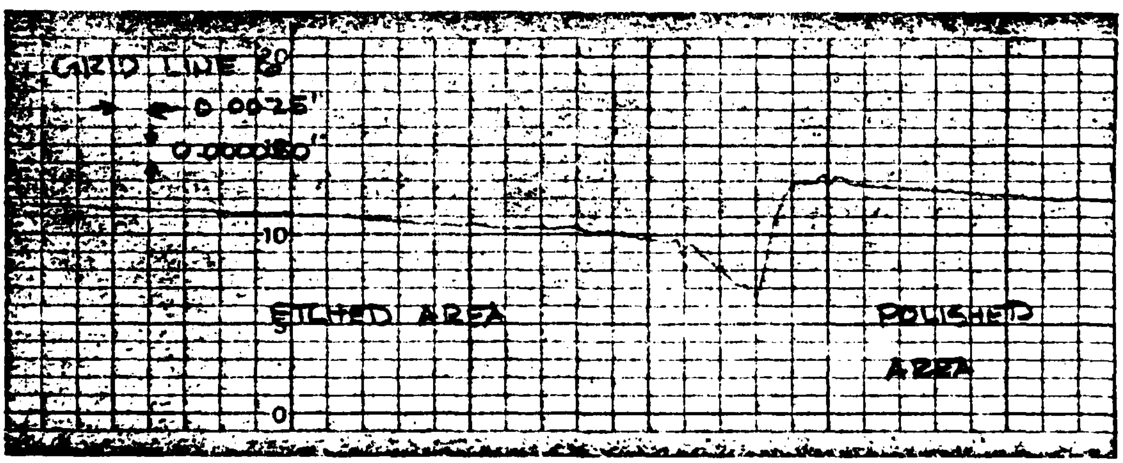
FIGURE 1

ORIENTATION

FIGURE 2


#79-2004
(RANK 1
GRID LINE 4
0.0025"
0.000050"
GRIDLINE 1
2
3
20
15
10
5
0
ETCHED AREA
POLISHED
AREA


GRID LINE 5
0.0025"
0.000050"
20
15
10
5
0
ETCHED AREA
POLISHED
AREA


GRID LINE 6
20
0.0025"
0.000050"
10
5
0
ETCHED AREA
POLISHED
AREA